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MANUFACTURING METHODS AND TECHNOLOGY
(MANTECH) PROGRAM

ISOTHERMAL ROLL FORGING OF T55 COMPRESSOR BLADES - PHASE II

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June 1980

FINAL REPORT

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Forging

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The objective of Phase II of this manufacturing technology program was to produce the 2nd stage blade of the Avco T-55 engine for static evaluation using the isothermal roll forge process. Blades were produced in AM-350 alloy using two roll-forge passes of the energy efficient, microprocessor controlled process. The blades met the fatigue, tensile and metallurgical requirements of Avco specifications.

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FOREWORD

This interim report on Phase II of Contract DAAG-46-76-C-0043 on "Isothermal Roll Forging of T55 Compressor Blades," covers work performed by Solar Turbines International from February 1978 to January 1980. Support under subcontract was provided by the Lycoming Division of Avco Corporation.

Phase I of this contract presented data in Interim AVRADCOM Report No. 77-11 to substantiate feasibility of the isothermal roll forging process. Phase II work produced second stage blades of the Lycoming T55 engine in AM-350 alloy. These blanks, produced by an automated forging process employing microprocessor control, met the tensile, fatigue and metallurgical properties as specified for the conventionally produced production blades. Lycoming indicated the blades met drawing requirements apart from a tendency to be 0.005 to 0.010 inch overgage near the root.

The controlling office for this project was the U.S. Army Aviation R&D Command with monitoring by the Army Materials and Mechanics Research Center (AMMRC). The Aviation R&D Command liaison engineer was Mr. G. Gorline. The technical supervision of this work was under Mr. Roger Gagne of AMMRC.

This project has been conducted as part of the U.S. Army Manufacturing Methods and Technology Program, which has as its objective, the timely establishment of manufacturing processes, techniques, or equipment to ensure the efficient production of current and future defense programs.

This program was conducted in the Advanced Manufacturing Technology Laboratory of the Solar Research Laboratories, with Dr. A.G. Metcalfe, Associate Director of Research as Technical Director. The Principal Investigator on this program was Mr. Fred K. Rose, Research Staff Engineer.

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1

INTRODUCTION

This Phase II Report presents work accomplished in the second phase of a three-phase program to apply isothermal roll forging to the manufacture of compressor blades. The Avco Lycoming T55 engine compressor blade has been selected for this manufacturing demonstration with Avco Lycoming providing engineering support under subcontract. The tooling and blade forging work reported was performed in the period February 1978 through August 1979, with blade evaluation work completed by Avco Lycoming in January 1980.

The first phase of the program was a demonstration of feasibility, and was described in AVRADCOM Report No. 77-11. Feasibility was defined as production of blades within 0.010 inch of the drawing envelope. This was achieved with typical standard deviations of the maximum airfoil thickness of less than 0.005 inch, although not all of the average dimensions fell on the nominal thickness. Preliminary cost data were presented and showed a reduction in the number of operations from 36 for present cold rolling to 11 (prior to the common finishing operations). Residual high cost areas in the isothermal roll-forging processes were identified as the multiple set-ups in the isothermal rolling mill and the individual hand machining of blanks.

The primary objective for the second phase of this program was to advance the process by production of blades within drawing tolerances by use of hard tooling. Secondary objectives were to reduce costs by a method to produce blanks economically and by consolidation of the multiple set-ups into a single processing step. Production from bar to blade (untwisted) in a single operation was felt to offer the built-in economics that would minimize costs. At the same time, it was necessary that the blades produced meet other drawing requirements. The Lycoming Division of Avco Lycoming undertook a preliminary evaluation including beehive fatigue tests to evaluate these requirements. The work described in this report covers the scope outlined above.

To meet the much tighter requirement on dimensions, work was performed in a 100,000 pound machine of different design from that used in Phase I. It provided much greater stiffness and stability. Modification to permit manufacture in a single step was undertaken. A microprocessor was added to control numerous parameters in the sequence required for the metal flow variations needed at each point along the length. These major changes delayed the start of roll-forging so that only one iteration was possible in the parameters instead of the multiple iterations planned. However, evaluation of these blades at Avco Lycoming indicated that the blades met drawing requirements apart from a tendency to be above gauge near the root. Based on this result, Avco has recommended that a sufficient quantity of blades be made available to allow for future engine tests.

2

FABRICATION OF COMPRESSOR BLADES

Current methods used to fabricate compressor blades are reviewed to provide a background for the introduction of the isothermal roll forging process. The review is designed to help identify the principal sources of cost so that the work can be planned to realize maximum cost savings. Major emphasis is placed on the potential cost savings because the large number of compressor blades required per engine makes these components a major contributor to jet engine costs.

2.1 CURRENT METHODS OF FABRICATION

The principal methods for fabrication of compressor blades are:

- Machining from solid
- Casting
- Hot die forging
- Cold roll forging.

Machining from solid stock is often used for small quantities of blades, but has had to be adopted to an increasing extent in recent years for production of blades in the more heavily alloyed materials. The latter include AM-350 steel and Inconel 718 that are difficult to forge to high performance blades. However, not only is machining expensive but is needlessly wasteful of both strategic materials and energy. Both of the latter experienced step-function types of cost increases fall in the year or two following the Energy Crisis of late 1973.

Casting may be more economical in material consumption and has been used to produce compressor blades but the individually cast blades do not offer an economic advantage for high performance engines.

Hot forging cannot form the precision shapes required for high performance engines and must always be followed by a certain amount of machining on all surfaces. Although the amount of metal to be removed is very much less than in machining from solid, the operations are expensive because they are precision rather than roughing cuts, and involve much hand labor to blend the machining cuts together. It is noteworthy that of the three critical problems identified by Avco in inspection of blades, viz.,

- Transverse grooving
- Root radii control
- Transition at root

two problems (transverse grooving and transition at root) are the result of hand operations in the manufacture of the blades.

The cold roll forging process is the most widely used method for production of steel and low alloy blades. It provides high quality, precision surfaces over much of the airfoil. Its major disadvantage is the large number of operations required. The number of roll forging passes increases rapidly with increasing alloy content. Up to 11 roll forging passes may be used, followed in each case by lubricant removal, annealing and relubrication. The number of roll forging passes is dependent on the rate of work hardening, thickness of leading edge (LE) and trailing edge (TE) and other factors, but will always be high. In addition, many other operations are required between passes including trimming and inspection, plus additional operations for root upsetting, twisting and broaching. Hand finishing to remove flash and blending of airfoil to platform are also significant contributors to cost both by increasing the in-process inspection and by reducing the yield of acceptable blades. Some of the principal operations in blade manufacture by this method are shown in Figure 1 for a cold-rolled compressor blade in 17-4PH steel used in a Solar turbine. In the case of the AM-350 alloy, an additional requirement is that the metal temperature be kept at 350°F or above to prevent austenite to martensite transformation.

2.2 THE ISOTHERMAL ROLL FORGING METHOD

The isothermal rolling and roll forging methods are based on use of refractory metal rolls or dies. The latter are heated together with the workpiece by a flow of controlled electric current. The control may be provided by feedback from a temperature sensor, although the process is inherently stable because there is a certain degree of self control. The latter arises because the size of the footprint between roll or die and workpiece seeks a constant value. When operating under constant current conditions, any change of gage causes a corresponding change in current density (temperature) and roll pressure that tend to maintain constant gage.

An important finding early in the development of the isothermal processes was that force feed could be used to prevent roll slippage at large reductions, and that this would increase the lateral spreading of the metal. One of the earliest applications of this concept was important to the present program. Round barstock of materials, such as 17-4PH steel, Ti6Al4V alloy and Rene' 95 superalloy were rolled from 0.375 inch diameter to an airfoil with 1.3 inch chord in a single pass. Figure 2 shows this operation in progress. The force feed is 6000 pounds with approximately 200 pounds of tension to maintain straightness.

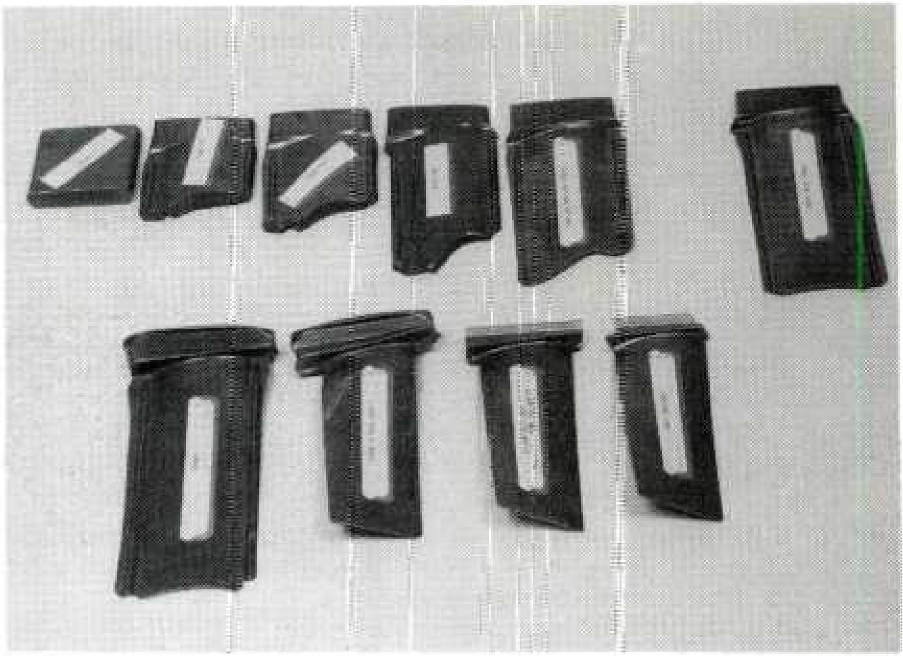


Figure 1. Some Stages in Cold Roll-Forging of Compressor Blades in 17-4PH Steel (#76-2679)

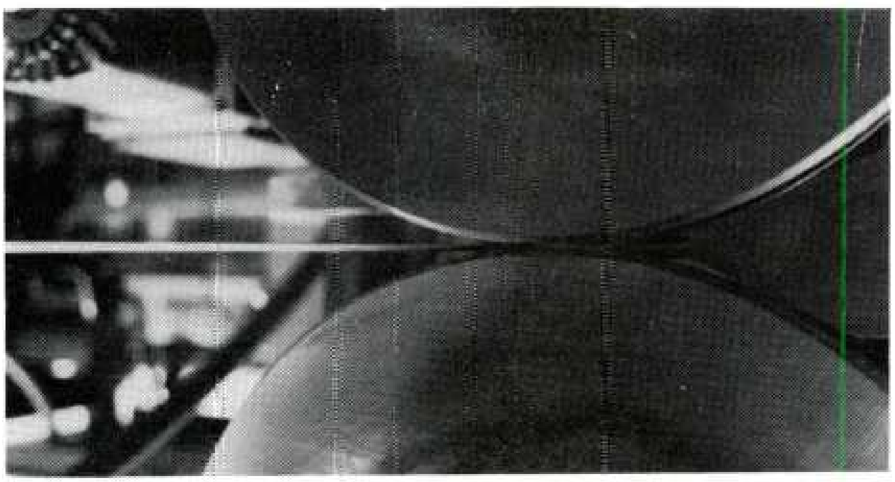
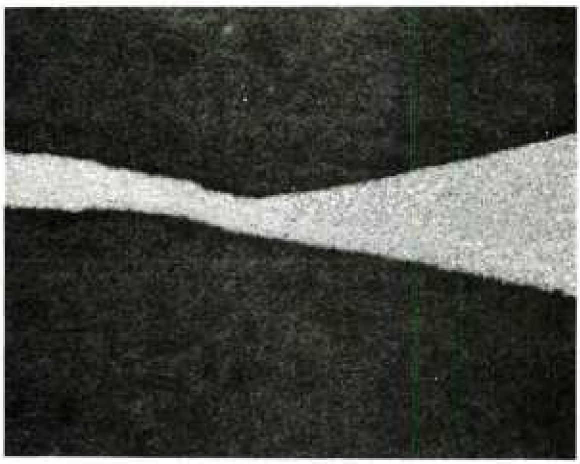


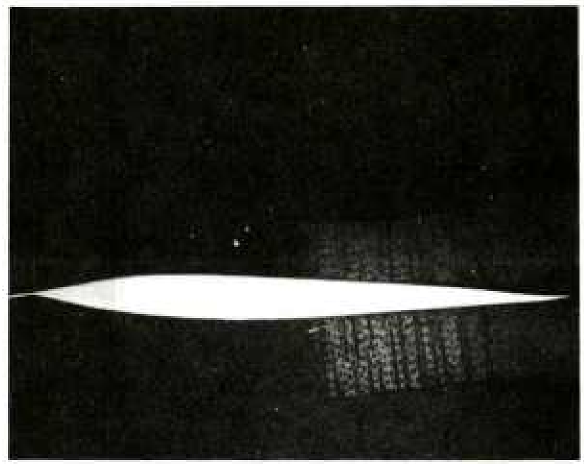
Figure 2. Single Pass Isothermal Rolling of 0.375 Inch Bar to a Contoured Airfoil With 1.3 Inch Chord. (Note bar emerging from force feeder guide on right.) (76-0961)

Important features of the airfoil rolling process were that excellent surface finishes were obtained (typically 16-32 rms) and that the contour was preserved up to the flash. Figure 3 shows a section of an airfoil to confirm the thin flash that can be produced from 0.375 inch diameter bar in one pass. Very thin LE and TE contours can be produced for the higher performance compressors required in advanced gas turbine engines.

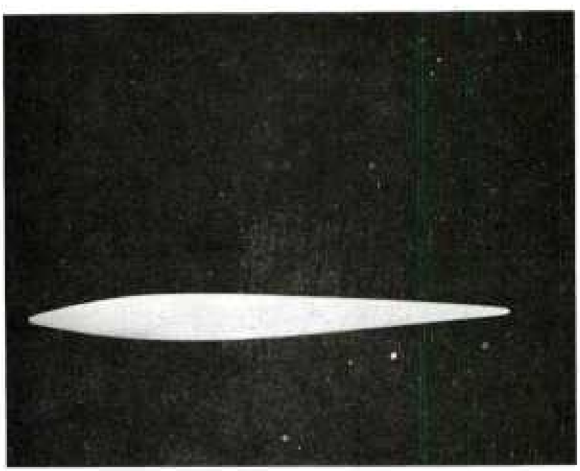
Figure 4 shows schematically one approach to the application of the isothermal roll forging technology to compressor blade manufacture.



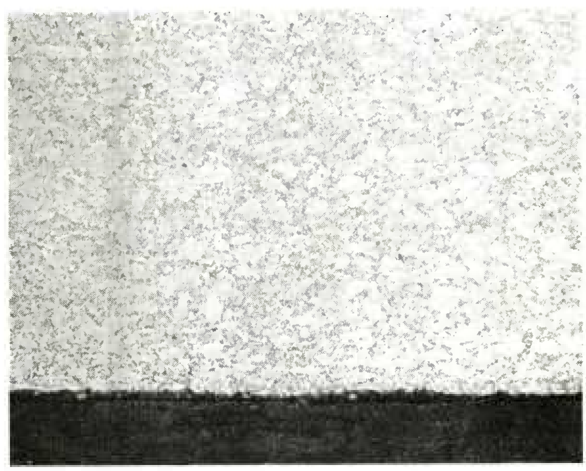
A. Leading Edge "As-Rolled"
0.0024 Inch Flash
Magnification: 75X



B. "As-Rolled" Airfoil
Magnification: 3.5X



C. After Sweco Finishing
Magnification: 3.5X



D. "As-Rolled" Surface
Magnification: 500X

Figure 3. Isothermal Rolled Ti6Al4V Bar (single pass) (#74-2000)

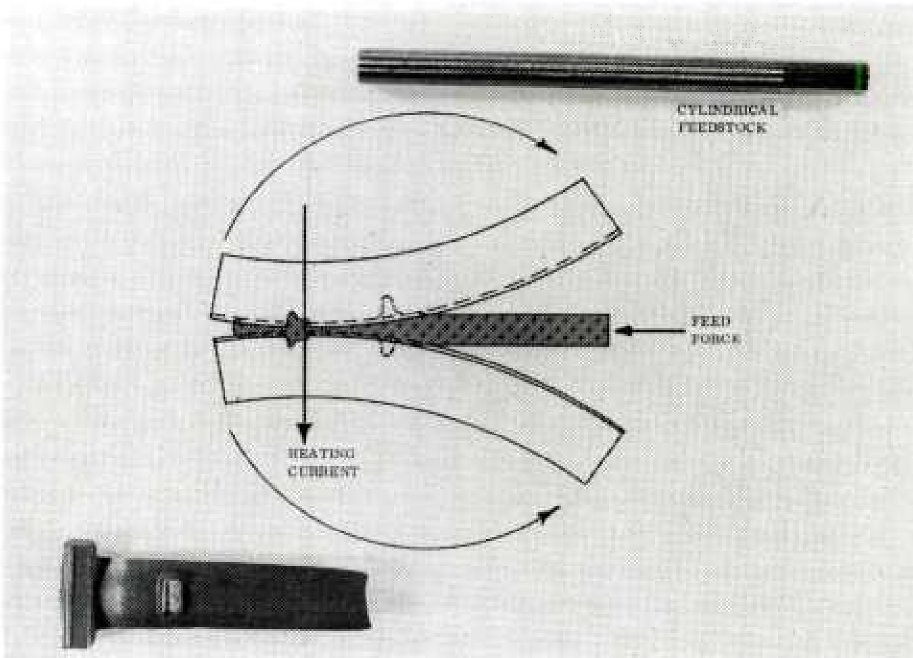


Figure 4. Isothermal Roll-Forging From 0.375 Inch Ti6Al4V to Simulated Mid-Span Shrouded Blade in One Pass

2.3 COST FACTORS

Preliminary analyses were made prior to the start of this program to identify the sources of cost savings and to make preliminary estimates of potential costs.

The major sources of cost savings were identified as:

1. Reduction in the number of operations
2. Reduction in the amount of hand work required
3. Reduction in the number of inspection steps as a result of #1 and #2
4. Reduction in scrap as a result of #1 and #2
5. Improvement in metal recovery
6. Reduction in energy consumed.

2.3.1 Reduction in Number of Operations

It is generally accepted have shown that manufacture of a net shape in a single pass leads to economy of operation. Some of the sources of cost reduction include:

1. Elimination of inter-operation handling

2. Elimination of inter-operation inspection

3. Reduction in clean-up required after each operation including: flash removal; lubricant removal; descaling; etc.

4. Reduction in preparation for subsequent operation including: stress relief annealing and/or heat treatment; lubricant application; etc.

5. Manufacture and maintenance of multiple tool sets

6. Mulitple tool set-ups and proofing

7. Increased scrap due to stack-up of tolerances from successive operations.

2.3.2 Reduction in the Amount of Hand Work

As pointed out earlier, the large reductions required to achieve the thin LE's and TE's needed in compressor blades are difficult to achieve in a cold rolling process. Stone* gives the minimum gage, t_{min}, achievable with steel rolls of diameter D and elastic modulus E when rolling a material with a constrained yield stress S_o, as

$$t_{min} = 3.58\mu \frac{DS_o}{E}$$

where μ is the coefficient of friction, This limiting gage is increased by work hardening (increased S_o) because this raises the roll pressure and hence the elastic roll flattening. For example, if S_o = 100,000 psi after work hardening, $\mu = 0.07$, D = 12 inch, then t_{min} = 0.010 inch.

A blade wih a TE thicknes of 0.010 inch would not thin below this amount. Elastic flattening of the roll (die) would decrease away from the TE leading to a condition as depicted in Figure 5. Gradual departure from the tolerance band (dashed) would occur until the nominal size was met back from the TE. Hand finishing to restore the tolerances to the band will be required after trimming of flash (assumed to be 0.010 inch in this example). Hand finishing to this extent is an expensive operation.

The isothermal roll forging operation can generate flash of 0.002 inch thickness. Now the amount of hand finishing is greatly reduced with fewer problems in holding contours. In addition, as shown in Figure 3, preliminary work indicates that automatic edge finishing operations may be possible with major reduction in labor and reduced scrap caused by lapses on the part of the operator.

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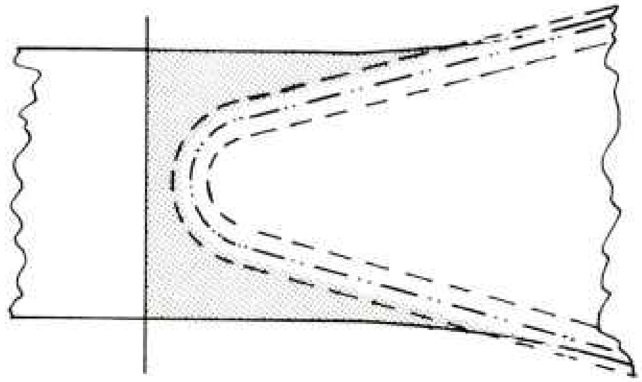
*Trans. ASME, Jour. of Basic Eng., December 1959, pp. 681-686)

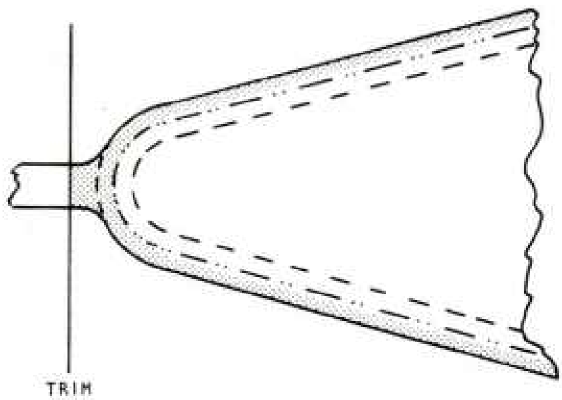


A. Operations in Cold Rolling

(1) Roll to within tolerance band leaving a 10-mil flash.

(2) Trim flash.

(3) Hand finish to outside limit of tolerance band by belt.



B. Operations in Isothermal Roll Forging

(1) Roll to outside of band leaving a 2-mil flash.

(2) Trim flash.

(3) Barrel finish to move airfoil within band and finish edge. Shaded area shows metal removed.

Figure 5. Comparison of Airfoil Edge Finishing Operations

There is another major advantage in elimination of hand operations. General Richard E. Merkling, Director of Aerospace Safety for the U.S. Air Force in a keynote address at the Third Annual Propulsion Materials Roadmap Review in Dayton, June 6, 1977, noted that undercuts from hand working TF34 fan blades had been responsible for at least one fatal crash. Engines and engine materials were the largest single cause of serious accidents. Figure 6, from his talk, shows that compressor blades and fan blades are a major source of accidents. Reduction of hand work may reduce costs and, at the same time, increase reliability.

2.3.3 Reduction in Number of Inspection Steps

As pointed out earlier, a major advantage of reducing the number of operations is that the attendant inspections are decreased. Inspection always presents a problem. With too little inspection, discrepant products may be carried forward to an excessive degree; whereas with too much inspection, the costs of the work becomes excessive and parts remain for longer periods in the shop.

On the other hand, bench-type inspection methods, such as guillotine gages and radii measurement tools may be indispensible to the efficient conduct of hand finishing work.

ENGINE MATERIEL PROBLEMS

- COMBUSTION CASES
- COMPRESSOR BLADES/VANES
- FAN BLADES
- MAIN BEARINGS
- ROTATING PARTS LCF
  - SPACERS
  - HEATSHIELDS
  - DISKS
- TURBINE BLADES/VANES
- QUALITY CONTROL

Figure 6. Principal Causes of Engine-Sources of Aircraft Accidents (see text for reference)

2.3.4 Reduction in Scrap

Low scrap production is achieved by tight control of each operation so that the individual probabilities are reduced. But, low scrap production can also result from reduction in the number of operations. It is expected that this result will be experienced with isothermal roll forging where the number of operations can be significantly reduced compared with competing methods.

2.3.5 Improvement in Metal Recovery

In a typical case, the cold rolled compressor blade shown in Figure 1 weighs 177 grams before broaching and is produced from the 367 gram blank shown in the first position. This is a metal recovery rate of 48 percent at this stage. Much lower metal recoveries are found in hot forged blades. Some improvement in metal recovery is expected in the isothermal roll forge process over existing methods.

2.3.6 Reduction in Energy Consumed

The energy requirement for producing a blade by the isothermal roll forge process is surprisingly low. At today's price of 7¢/kW hr the electrical energy consumed to produce a T55 2nd stage blade is approximately 34¢, i.e., about 2 percent of the estimated blade selling price. A roll forging pass consumes approximately 2.05 kW hr and the hot coining operation 0.8 kW hr.

The operations employing preheat ovens and interpass annealing furnaces which are required for conventional cold roll forging are unnecessary with isothermal roll forging.

3

WORK ACCOMPLISHED

The purpose of this program is to establish isothermal roll forging as a low-cost manufacturing method for compressor blades. Two phases have been completed. Phase I* demonstrated the feasibility of producing compressor blades for axial flow turbine engines in precipitation hardening stainless steel (AM-350) and in titanium alloy (Ti6Al4V). The objective of Phase II is to establish a manufacturing process for the second stage compressor blade of the Lycoming T55-L-11A engine based on the methods and procedures demonstrated in Phase I. The original plan identified nine tasks that needed to be completed to establish a viable manufacturing process. The nine tasks are:

Task 1 - Blade and Tool Material

Task 2 - Fabrication of Blade Preforms

Task 3 - Rough Roll-Forging

Task 4 - Intermediate Operations

Task 5 - Final Roll Forging

Task 6 - Evaluation of Forged Blades

Task 7 - Final Operations

Task 8 - Evaluation of Finished Blades

Task 9 - Process Specifications

The report presents the procedures employed and the results obtained in Phase II based on the above format.

3.1 TASK 1 - MATERIALS

This task involves the selection, procurement and characterization of the blade forging stock and forge die materials.

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* Rose, F.K., Metcalfe, A.G., "Isothermal Roll Forging of T55 Compressor Blades, AVRADCOM Report No. 77-11, December 1977.

3.1.1 Blade Forging Stock

At the start of the program it was hoped that enough residual AM-350 material would be available from Utica Division to enable direct comparisons with conventionally manufactured blades made from the same heat. This course was followed in Phase I, but unfortunately, sufficient material from this heat was not available for the subsequent work.

The AM-350 material was purchased for Phase II from Universal Cyclops Specialty Steel Division. (Universal Cyclops was the supplier for Phase I material obtained from Utica Division.) The material was ordered in the form of 0.250 x 0.500 inch rectangular bar in 12-foot random lengths in the hot rolled solution treated and pickled condition (Condition H). This heat treat condition would provide maximum formability for cold roll forming of the preform. In this condition the material has a yield strength of approximately 60,000 psi with a minimum elongation in 2 inches of 38 percent and a hardness of Rc20. However, the material was delivered in the equalized, overtempered and pickled condition, in which condition the yield strength and hardness were determined by Solar to be 175,000 psi and Rc42. A minimum strength level of approximately 160,000 psi was established in Phase I to avoid preform buckling during root injection, and it was planned to heat treat the Condition H to this level after cold roll forming. As discussed below in Section 3.2, it was necessary to anneal this material to enable cold roll forming of the blade preforms.

The vendor material certification report for the Phase II material is shown in Figure 7. The chemical composition, heat treated tensile properties and hardness all meet AMS5745A as required.

The microstructure of the as-received AM-350 feedstock is shown in Figure 8. The material has fine grains which are elongated in the rolling direction. The structure consists of dark etching islands of delta ferrite, containing finely precipitated austenite, in a lighter etching matrix of martensite. Carbide precipitation at the grain boundaries does not appear excessive. Figure 9 shows the microstructure of the same heat of material (8C3744R2) after the standard hardening heat treatment of:

Harden 1710 $\pm$ 25°F (30 min), air cool,

+ subzero cool -100°F for 3 hours,

+ temper 1000 $\pm$ 10°F for 3 hours.

The heat treated microstructure appears normal, i.e, the light etching delta ferrite islands are in low concentration and the carbides are well dispersed throughout the martensite matrix.

The mechanical properties were evaluated by measuring the room temperature tensile properties in several heat treat conditions. These data are reported below in Section 3.2.

UNIVERSAL-CYCLOPS SPECIALTY STEEL DIVISION LOS ANGELES
TITUSVILLE PLANT – TITUSVILLE, PA. 16354
MATERIAL CERTIFICATION REPORT

CYCLOPS CORPORATION

GRADE AND DESCRIPTION: UNITEMP 350 EQUALIZED, OVERTEMPERED, PICKLED

SPECIFICATION: AMS5749A

SIZE: .250" X .500" X 12 FT. R/L

SHIP TO:

SOLAR DIVISION
INTERNATIONAL HARVESTER
P.O. BOX 80966
2200 PACIFIC HIGHWAY
SAN DIEGO, CA. 92138
ATTN: PURCH. DEPT.

CUST. ORDER NO. 7672-42413535
MILL ORDER NO. 58951
DATE SHIPPED 5-12-78
QUANTITY & WEIGHT 94 Bars - 546#

MELTED IN THE U.S.A. — CHEMICAL ANALYSIS

HEAT NO	C	Mn	Si	S	P	Cr	W	V	Ni	Mo	Co	Cu
83374 82	.093	.62	.14	.007	.017	16.70			4.20	2.67		

HEAT NO.	Sn	Pb (PPM)	Al	Ti	Fe	B	Zr.	Cb /Ta	La	Bi (PPM)	N	
											.097	

		TENSILE PROPERTIES					STRESS RUPTURE PROPERTIES					
CODE	IDENTIFICATION	KSI TENSILE	KSI 2 YIELD	KSI 02 YIELD	% EL	% RA	TEMP. °F	KSI STRESS	TIME HR.	% EL		IMPACT ft. lbs. V N CHARPY
*		178.0	153.0		21.4	61.0						

CODE	HEAT TREATMENT	HARDENABILITY	GRAIN SIZE
*	CAPABILITY AFTER: 1600F 3 HRS. WATER (-100F 3 HRS) + 1750F 1 HR. WATER (-100F 3 HRS) + 1000F 3 HRS. AIR	* 39.0 RC	

HARDNESS. 332/375 BHN
REMARKS.

SWORN TO AND SUBSCRIBED BEFORE ME
THIS 12th DAY OF May 1978
Bruce E. Kline
BRUCE E. KLINE, Notary Public
Titusville, Crawford Co.
My Commission Expires June 16, 1981

I certify that this TEST REPORT is a true & correct copy of our laboratory records.

By P. L. Williams
Quality Control Representative

Figure 7. Phase II Material

A.

Longitudinal

Long Transverse

B.

Longitudinal

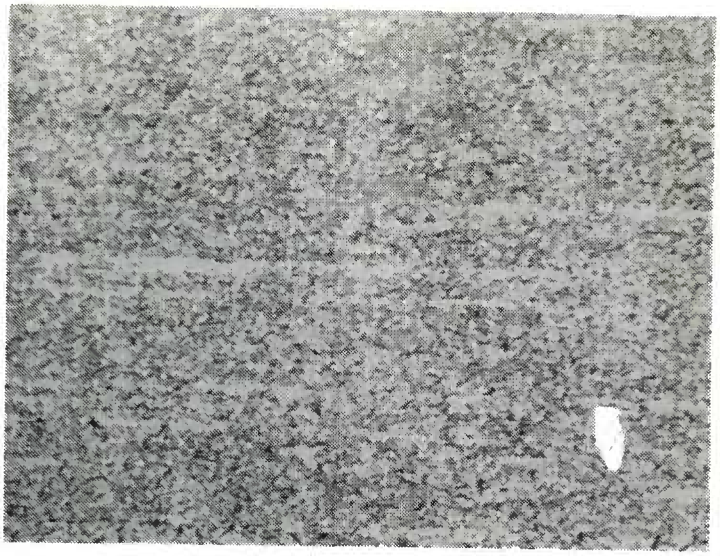
Short Transverse

C.

Long Transverse

Short Transverse

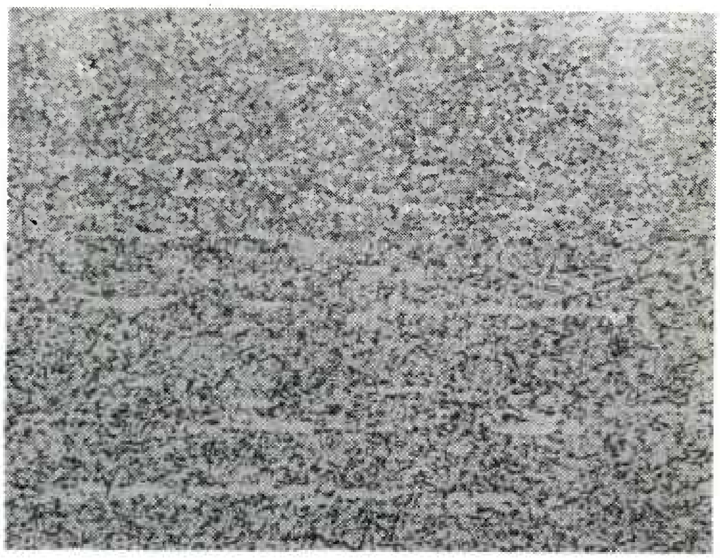
Figure 8. Orthogonal Sections Showing Microstructure of As-Received AM-350 Feedstock. Mill Heat Treatment: Equalized and Overtempered. Etchant: Marble's (10 sec). Magnification: 500X



A.

Longitudinal

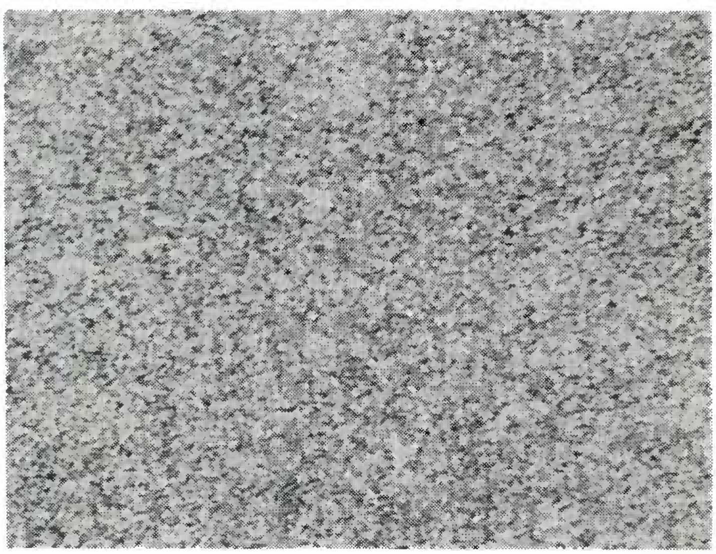
Long Transverse



B.

Longitudinal

Short Transverse



C.

Long Transverse

Short Transverse

Figure 9. Orthogonal Sections Showing Microstructure of AM-350 Feedstock.
After Heat Treatment: 1710°F + 32°C + 1000°F
Etchant: Marble's (10 sec). Magnification: 500X

A layer of delta ferrite 0.003 inch thick was found on one face of the AM-350 feedstock, and appears as the white phase in the as-received feedstock shown in Figure 10A. The presence of the delta ferrite layer was not considered cause for rejection because all traces were caused to disappear by 20 percent or more deformation imparted by an isothermal roll forge pass as shown in Figure 10. This was verified in the subsequent blade forging work.

3.1.2 Forge Die Materials

The selection of die material involved a detailed analysis of the metallurgy of molybdenum alloys. The alloys TZM and MT-104, in the forged condition, have been found to be the best commercially available die materials for isothermal roll forging. With dies of these alloys, roll forging can be performed on materials as diverse as Rene' 95 (200,000 psi at 1200°F) or HS188 (21,000 psi at 2000°F). However, the "window" for safe operation could be widened if a stronger die material were available. the most important properties of a die material for isothermal roll forging are:

1. High yield strength at high and intermediate temperature.
2. Formation of conductive glaze in the presence of graphite lubricants.
3. Electrical and thermal properties similar to TZM.
4. Ductility at room temperature to withstand thermal stresses on cool-down and operating stresses.

Early work in molybdenum alloy development showed that solid solution strengthening was not as effective as dispersion phase hardening in strengthening the metal. As dispersion phase hardening is largely independent of composition, high strength can be achieved only by improved thermal mechanical processing. Hence, any new alloy will have the same limitations as TZM, that is the difficulty of getting sufficient warm or cold work into the structure so that finer dispersions and higher strength can be realized. This claim is illustrated by work of Klopp, et al* where the strength of Mo-0.5Hf-0.3C alloy ranged from 160,000 psi to 70,000 psi depending whether the alloy was worked at 2500°F or 2800°F. The problem of improved die material availability is not that new compositions are needed but that improved methods are required to put more warm work into alloys of the same or similar compositions. With the exception of not having high strength at intermediate temperatures, the alloys TZM and MT-104 have been shown to possess the properties needed for die materials. Extensive alloy development probably would yield an improved alloy. However, we believe existing alloys when properly worked will meet the requirements for the present blade forging program. We reviewed our requirements with three producers and placed an order with GTE Sylvania because of their willingness to do special thermal mechanical processing of MT-104 alloy to achieve maximum strength at our use temperature.

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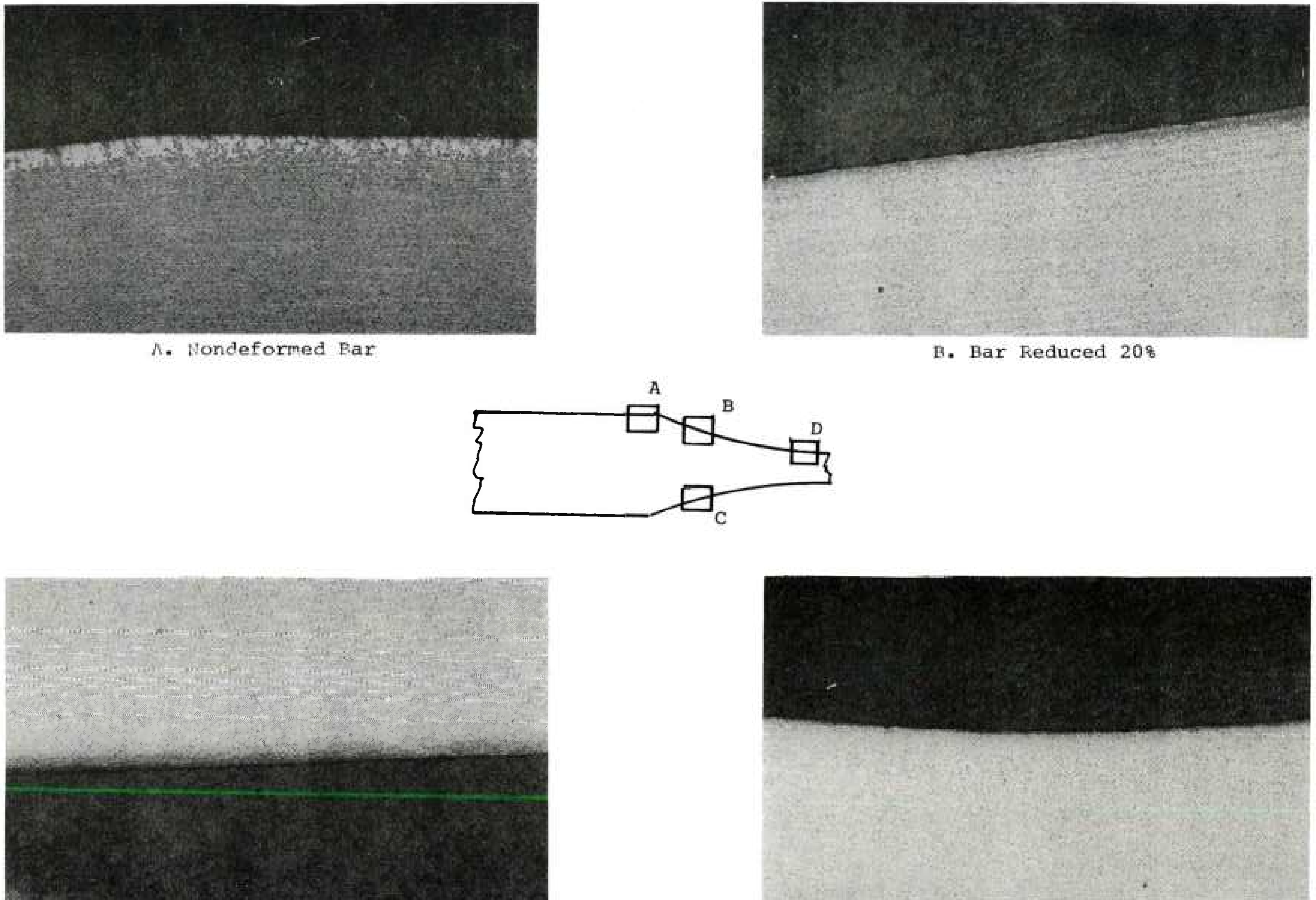
* Klopp, W.D., Raffo, P.L., and Witzke, W.R., "Strengthening of Molybdenum and Tungsten Alloys With HfC, J. Metals, Vol 23 , No. 6, June 1971. pp 27-38.



A. Nondeformed Bar

B. Bar Reduced 20%

C. 20% Reduction Opposite Face

D. Bar Reduced About 80%

Figure 10. Microstructure of AM-350 Feedstock Showing Affect of Roll Forge Deformation on Delta Ferrite Banding. Magnification: 50X

The microstructure of a representative sample of MT-104 molybdenum alloy die facing material is shown in Figure 11. The sample was taken from 0.63 in. by 2.25 in. wide bar after isothermal roll bending at 2300°F. The microstructure appears normal for cross-rolled plate, and there is no evidence of recrystallization due to the hot bending operation. The structure consists of grains of normal size with considerable retention of warm work. The grains are flattened in the short transverse direction with elongation in both the long transverse and longitudinal directions. The principal rolling direction was longitudinal.

Room temperature hardness of the die facings was measured in the as-received condition and again after hot roll bending at 2300°F. An increase in hardness from 248 to 260 BHN suggests additional precipitation of carbides occurred during hot bending. The composition of the molybdenum powder and the sintered preforms used to make the forged die facing are shown in Figure 12.

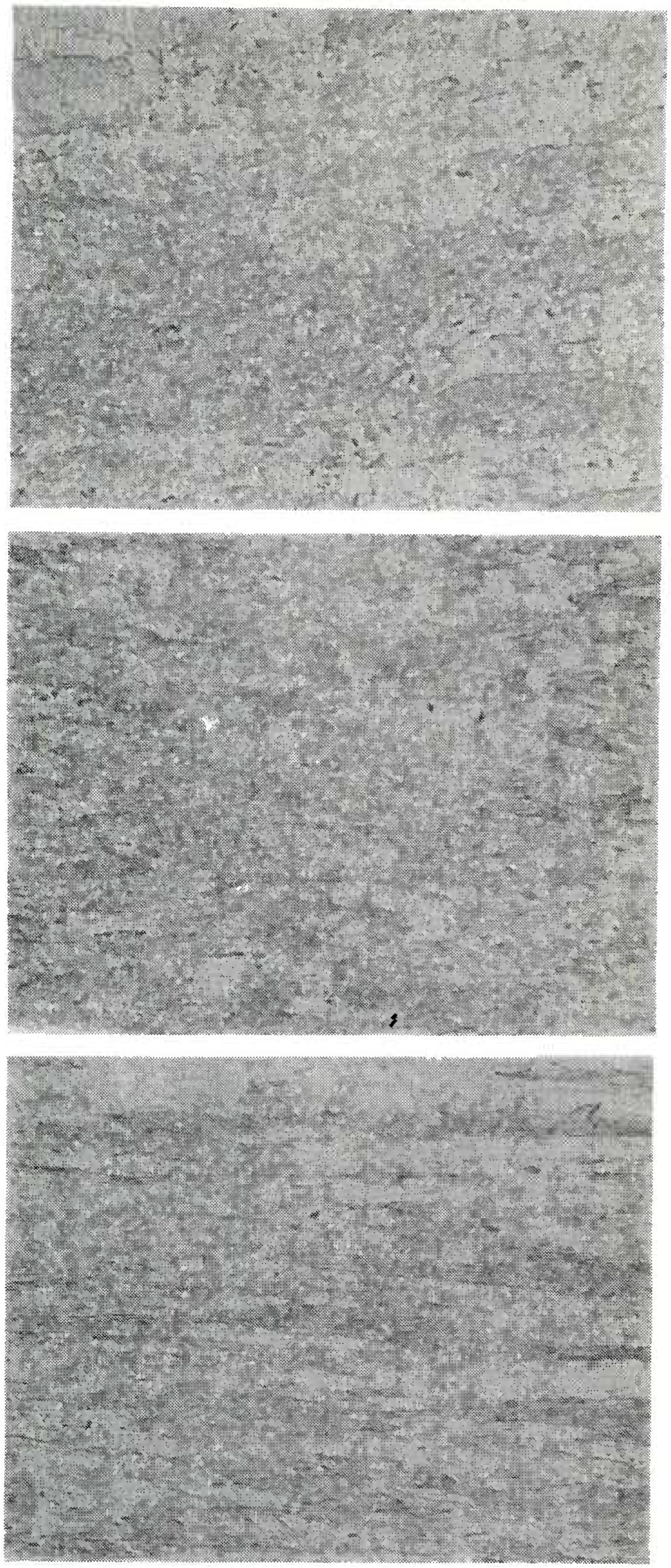
3.2 TASK 2 - PREFORM

The basic design of the blade preform was established during Phase I and is shown in Figure 13. The contoured surfaces were generated in Phase I by a combination of turning and milling operations. The plan in Phase II was to produce the desired shape by a low-cost cold-roll forming operation. The Turk's Head roll cluster designed for this purpose is shown in Figure 14. It consists of a rigid welded steel frame with four hardened steel rolls operating as opposed pairs. The arrangement of the rolls is shown in Figure 15 as viewed through the workpiece entrance port. The rolls were made from A-2 tool steel and were hardened to 58/60 Rc. Each roll contains a bronze bearing that turns on a 1-inch 4140 steel shaft.

The first forming tests were made by drawing 1/4 x 1/2 in. mild steel through the roll cluster by means of a tensile machine. The axial load required was 2800 pounds and the contours were well formed. AM-350 in the as-received condition (equalized and overtempered) was rolled equally well but the force required was 5800 pounds. The transverse section of the cold rolled AM-350 blade preform is shown in Figure 16. A defect in one of the rolls (see Fig. 15) caused the irregularity shown at one corner of the as-rolled preform. The irregularity was eliminated by replacement of the defective roller.

Macroetching of the cold formed section clearly shows strain induced transformation. This transformation was not detrimental to the mechanical properties as a tensile yield strength of 184,000 psi with reasonable ductility was measured after tempering the rolled preform at 1000°F.

However, after rolling three 12-foot lengths of this feedstock dimensional control was lost. The high roll separation force needed to roll the 175,000 psi material caused the roller bearings to fail.



A.

Longitudinal

Long Transverse

B.

Long Transverse

Short Transverse

C.

Longitudinal

Short Transverse

Figure 11. Microstructure of Molybdenum Alloy MT-104 Die Facings
Etchant: Murakami's (5 sec). Magnification: 200X

GTE SYLVANIA SPECTROGRAPHIC LABORATORY
TOWANDA, PENNSYLVANIA

Plate Number DR   Quantitative Analysis Report   cc: Quality

Date Received ______   Date of Analysis ______ ______

Sample MT-104 Alloy Powder   Emission ______   Atomic Absorption ______

Analyst ______

Approved By [illegible]

Mix 888   (Sintered Analysis)

ppm

Al	<4						ppm-C	134		
Ca	2						O_2	233		
Cr	<1						N_2	6		
Cu	1									
Fe	<5									
Mg	<1									
Mn	1									
Ni	<1									
Pb	<2									
Si	8									
Sn	5									
W	58									
Na	<8									
K	<15									
Ti	.49									
Zr	.068									

REMARKS:

Figure 12. Chemical Analysis of MT-104 Powder and Sintered Preform Used to Make Facings for Blade Forge Dies

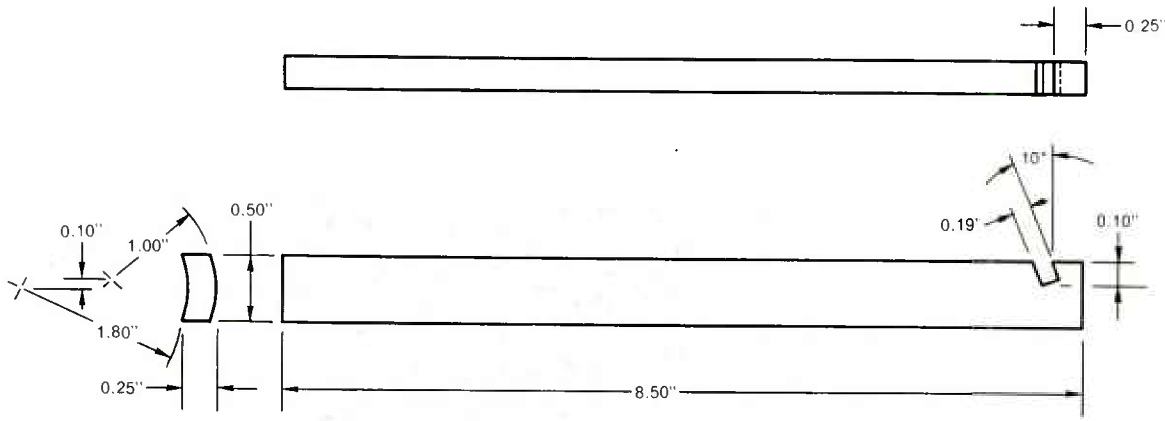


Figure 13. Design of Preform

Two actions were taken:

1. The bearings were replaced with a beryllium copper alloy (Berylco 25).

2. The AM-350 feedstock was annealed prior to rolling

One hundred and twenty lineal feet of the equalized and overtemered AM-350 feedstock were annealed to facilitate cold rolling into the simple preform section needed for blade forging. The following procedure was used to prepare the blade preforms.

1. Twelve-foot lengths of 1/4 x 1/2 in. AM-350 feedstock were cut into 3-ft lengths to facilitate handling.

2. After degreasing and attachment of thermocouples, the bars were charged into a preheated electric air atmosphere furnace and were held at 1825 ± 25°F for 30 minutes.

3. The bars were withdrawn from the furnace, and allowed to air cool on a brick topped table. The bars cooled to below red heat in less than one minute.

4. Descaled and passivated by a sequence through hot Kolene, $HF\text{-}HNO_3$, HNO_3 and water rinse.

5. The bars were lubricated with MAGNU DRAW 40* and cold rolled into the preform section by drawing through the Turk's Head roll cluster at a draw speed of approximatley 0.5 foot per second.

6. Equalized 1400 ± 25°F for 3 hours, air cooled to room temperature, then overtempered at 1050°F for 4 hour.

*Magnus Division of Economics Laboratories, Inc., White Plains, NY

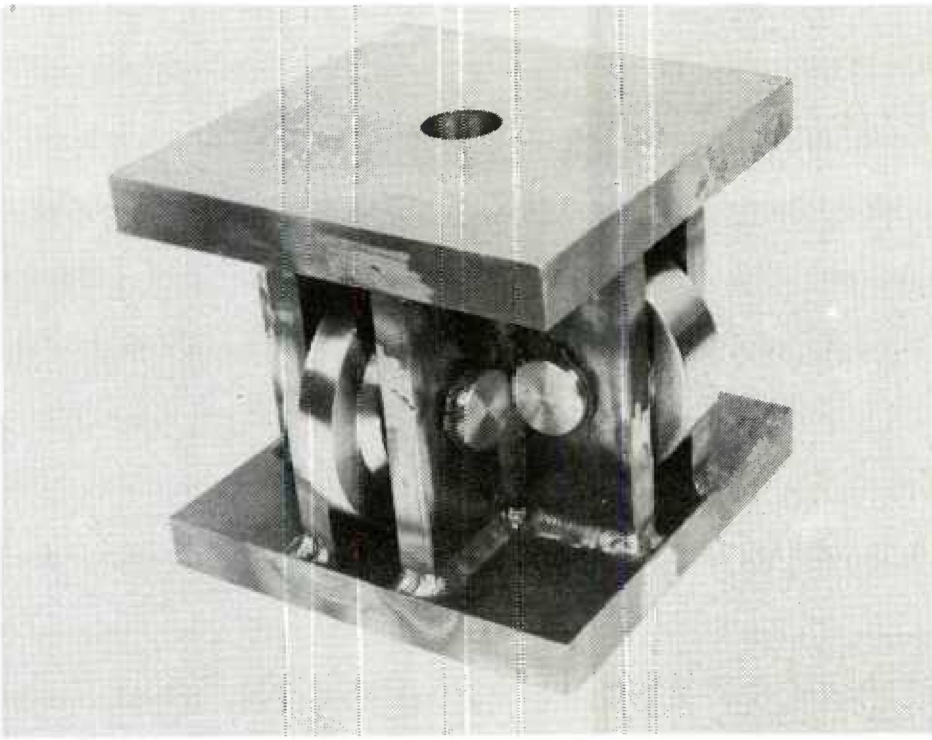


Figure 14. Turk's Head for Cold Draw Roll Forming of Blade Preforms (#78-3238)

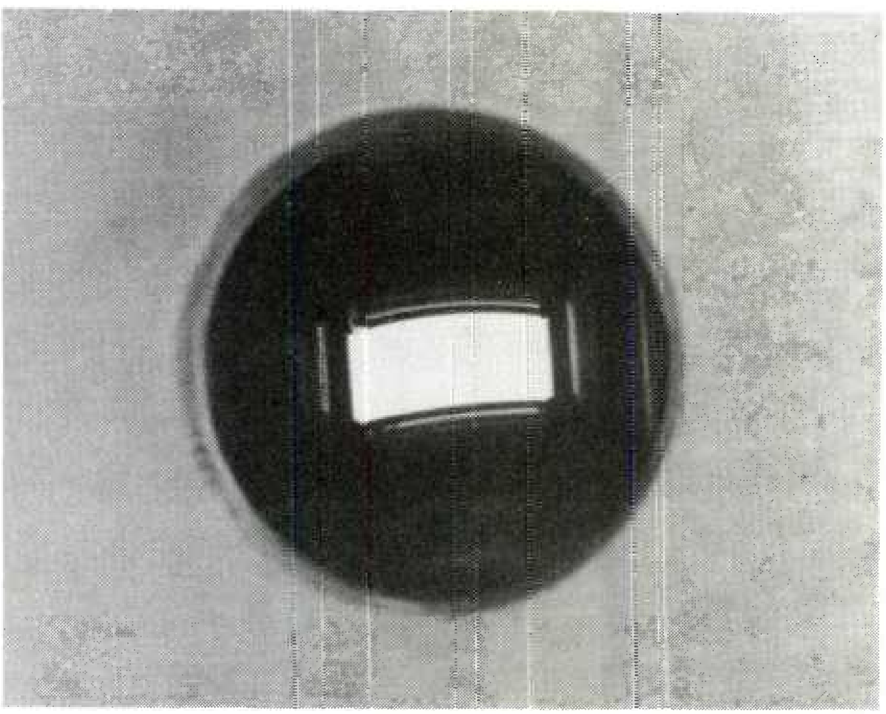
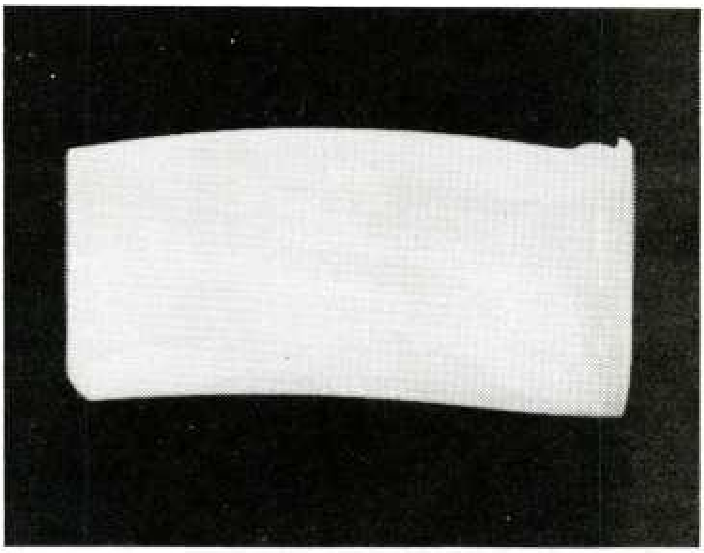
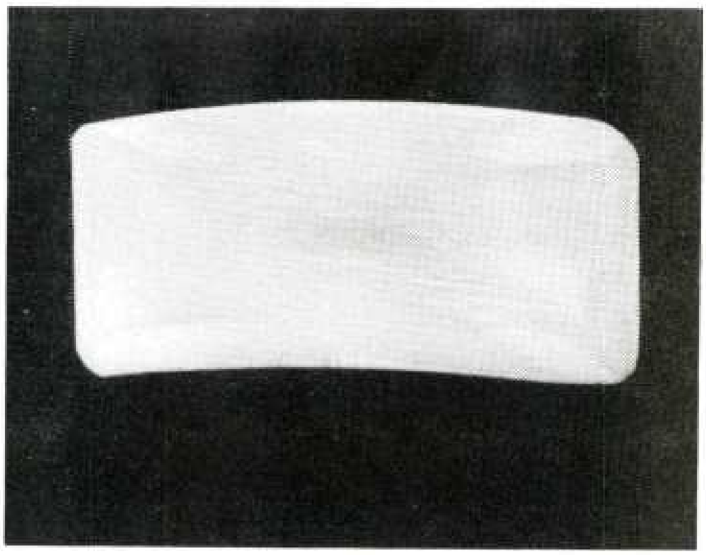


Figure 15. Turk's Head Roller Gap (#78-3239)



A. As-Rolled

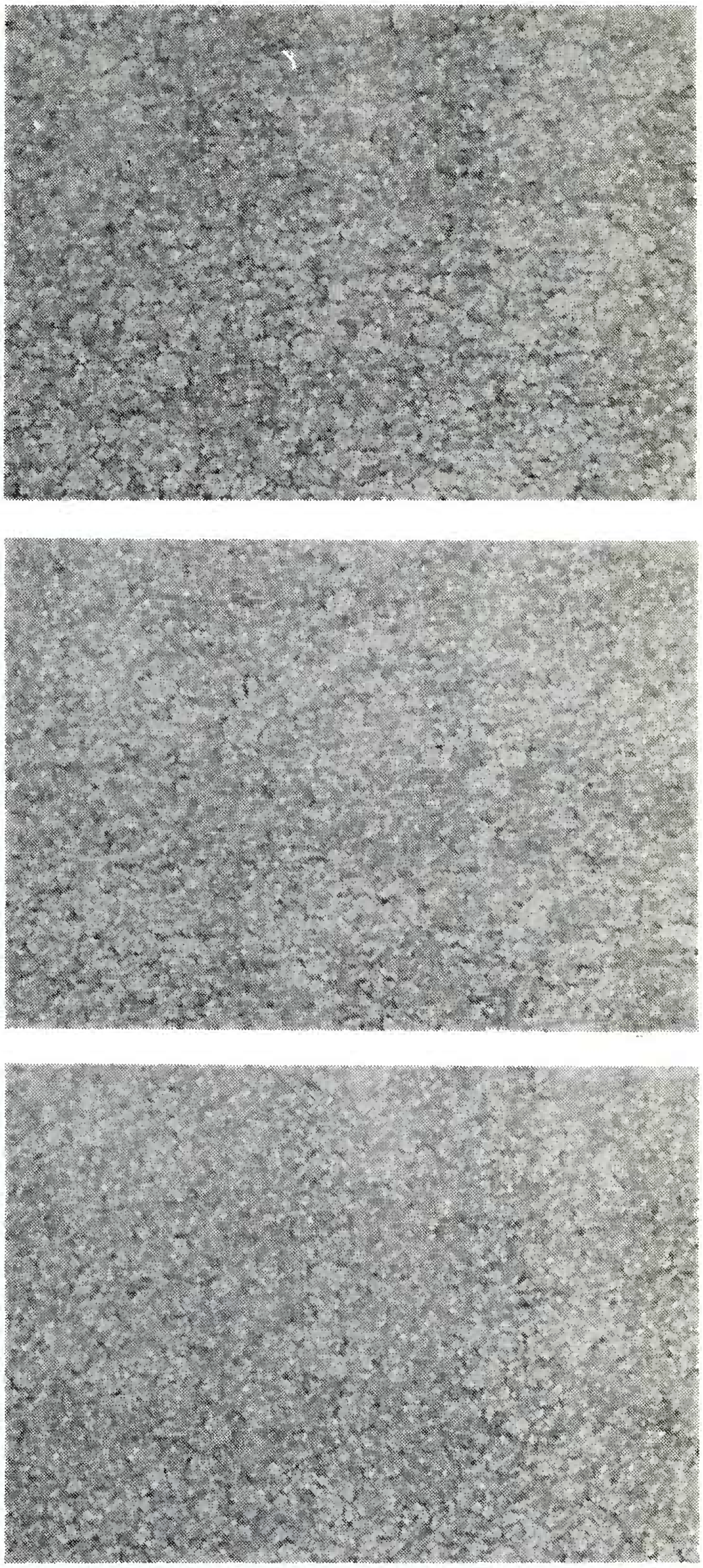


B. Corners Radiused

Figure 16. Transverse Section of Cold-Rolled Blade Preform
Etchant: Marble's (10 sec). Magnification: 6X

The dimensional control of the cold rolled preform was excellent. The maximum thickness, measured from the concave to convex surfaces, was 0.233 inch with a standard deviation of 0.00046 inch over 120 linear feet of rolled preform. There was no evidence of bushing wear in the Turk's Head rollers.

The microstructure of the AM-350 preforms is shown in Figure 17. This figure shows the material after the processing steps of annealing, cold draw/roll forming, equallizing and overtempering. The principal change from the as-received structure is that the grains are more equiaxed and the banding of delta ferrite has been broken up. The carbide distribution in Figure 17 appears normal for the equalized and overtempered condition.



A.

Longitudinal

Long Transverse

B.

Longitudinal

Short Transverse

C.

Long Transverse

Short Transverse

Figure 17. Orthogonal Sections Showing Microstructure of AM-350 Feedstock. After Annealing, Cold Draw/Roll Forming of Preform Equalizing and Overtempering. Etchant: Marble's (10 sec);Magnification: 500X

The tensile properties of the AM-350 feedstock in the as-received condition and after various heat treatments and cold forming are listed in Table 1. Annealing put the material into a readily formable condition; cold draw/roll forming to the preform shape caused some strain hardening with little or no loss of ductility; and subsequent heat treatment restored considerable yield strength while retaining good ductility.

Table 1

Tensile Properties of AM-350 Blade Feedstock
in Selected Heat Treat Conditions

Specimen: 0.200 In. Dia x 1.0 In. Gage; 2 Each Condition
Instron Test Machine; Room Temperature; Strain Rate 0.05 in/in/min

	Yield Strength at 0.1% (ksi)	Tensile Strength (ksi)	Elongation (%)	RA (%)
1. As-Received (Equalized and Overtempered	178.3 171.5	199.0 199.7	10.6 11.1	36.8 39.1
2. Annealed	34.9 48.0*	200.9 196.3	19.5 18.8	55.5 58.9
3. Condition 2 Plus Cold Draw/Roll Formed	65.0 81.0	167.9 209.2	20.0 16.6	61.4 53.5
4. Condition 3 Plus Equalized and Overtempered	148.2 146.2	166.7 163.5	15.6 14.7	49.0 49.3

*High yield value because specimen was inadvertently preloaded to 1.5% elongation

The preforms were finished by cutting to length with an abrasive cut-off machine, followed by tumbling in Sweco vibratory finishing machine. The notch near one end was gang-milled to provide an attachment point for the application of front tension (See. Section 3.3.1).

3.3 TASK 3 - ROUGH ROLL FORGING

3.3.1 Forging Machine

The isothermal roll forge machine used to produce the blades in Phase II is shown in Figures 18 and 19. This machine is rated at 50 tons die squeeze and 25 kiloamperes heating current. It employs roll forge dies 2 inches in width with a 6.730-inch radius, that rotate through an arc of 45 degrees to produce a blade. The machine consists of a rectangular steel frame, open top and bottom, which surrounds two yokes each of which contain a pivot shaft that supports the dies. Hydraulic cylinders mounted at each end of the frame apply forces to the yokes which bring the dies together at the center of the machine. The rectilinear motion of each yoke is guided by four dovetail slides mounted between the yoke and the machine frame. Each pivot shaft is constrained in its yoke by two tapered roller bearings. Each shaft extends to the rear of the machine where rigid connection is made to a gear box which translates with the yoke. The two gear boxes are driven by a common motor by means of two flexible shafts. One revolution of the motor produces a precisely synchronized motion of 0.00265 inch of the die faces.

A schematic diagram of the machine showing the positions of the principal components is illustrated in Figure 20. The dies are mounted on die support blocks which are electrically insulated from the pivot shafts. The workpiece and dies are heated by electric current (I) that enter through one of the die support blocks, passes through the dies and workpiece, and exits through the other die support block. The desired workpiece temperature is maintained by means of an optical pyrometer/controller that sights the workpiece and modulates the heating current. Figure 20 shows the initial position of the dies for blade forging. The die root pockets are aligned, the die support blocks are hard against the angular stops, and the lower feed ram is fully retracted. The sequence of events for blade forging proceeds as follows:

1. Insert workpiece into tip of lower nozzle against top face of feed ram.

2. Initiate Microprocessor Controller

   a. Upper nozzle descends onto free end of feedstock and against the stops.

   b. Upper feed ram descends with low force against upper end of workpiece.

   c. Left die moves against workpiece and against stop. Right die then moves against workpiece at low force.

   d. Heating current is initiated at low level. Optical temperature feedback adjusts current to raise workpiece to forging temperature in about 5 seconds.

   e. While maintaining the desired forging temperature, die squeeze force (F_S) is increased gradually to a desired level in about 20 seconds causing the dies to close upon the workpiece.

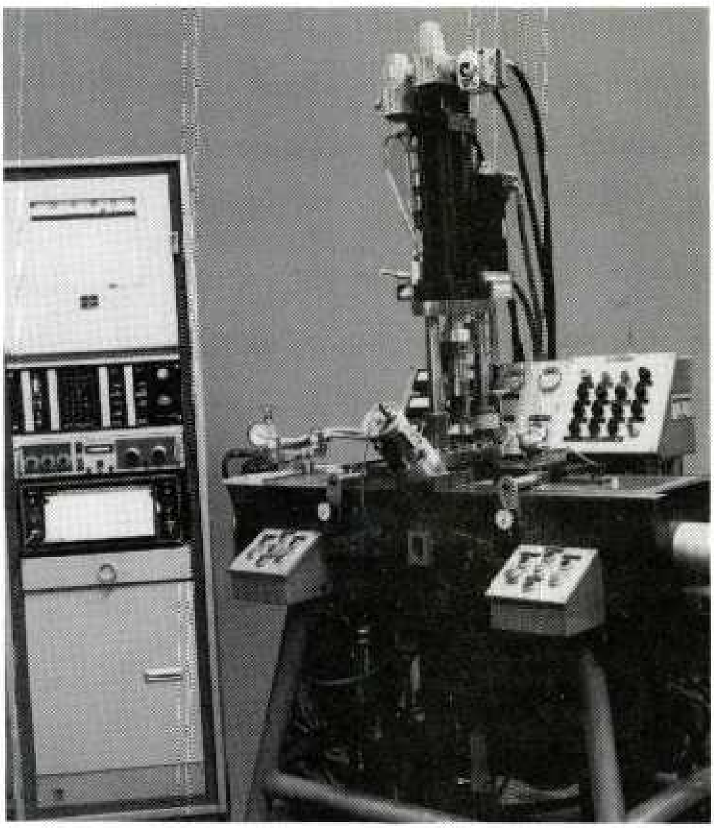


Figure 18. Isothermal Roll Forging Machine (#79-5315)

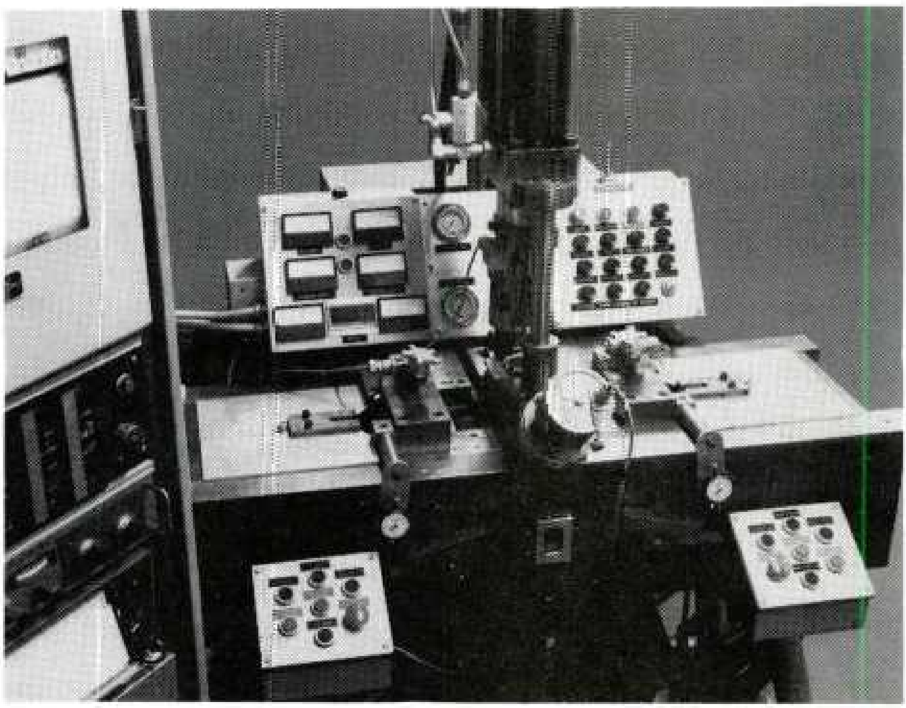


Figure 19. Operator's View of Isothermal Roll Forging Machine (#79-5314)

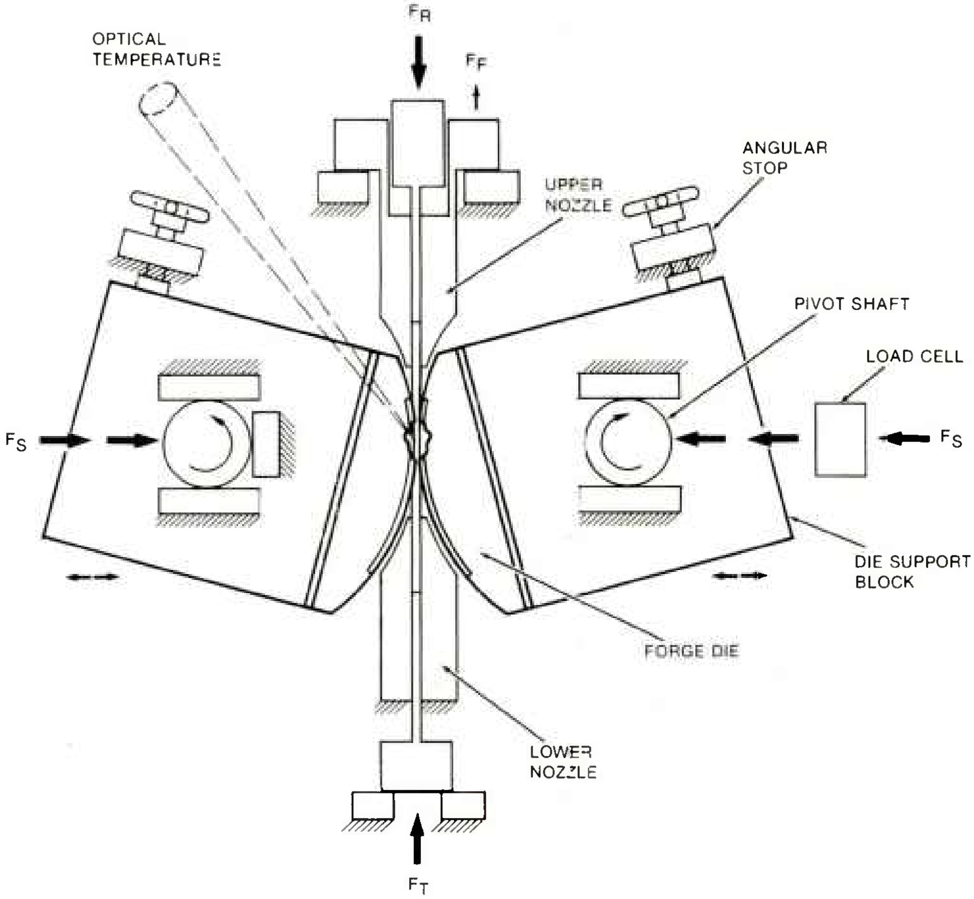


Figure 20. Schematic Diagram of Blade Forging Machine

f. Root injection force (F_R) is applied at a controlled rate causing the upper portion of the workpiece to move downward and to be upset within the root pockets of the dies. Root formation takes about 20 seconds.

g. When root formation is complete force F_R is removed and the front tension force F_F and the tip feed force F_T are applied and die rotation is initated and the airfoil is roll forged while maintaining: (1) die closure by means of maximum squeeze force F_S; and (2) desired forging temperature by means of optical feed back.

h. When the airfoil is complete, the heating current is extinguished, tip feed ram retracted, die rotation stopped and dies retracted. The finish forged blade continues to move upward with the ascending upper nozzle where it is unloaded from the machine.

3. Relubrication of the dies and their return to the root forge position completes the forging cycle.

The tip feed force F_T is applied to the tip end of the workpiece to which the airfoil is being roll forged. This force assists the workpiece entering the bite of the roll forge dies, prevents die slippage at the large thickness reductions achieved, influences lateral spreading and flash formation, and controls axial elongation of the airfoil. Forces in the range of 600 to 2200 pounds are applied by means of a hydraulic cylinder mounted on the underside of the machine.

On the upper side of the machine two vertically applied force systems are employed. One moves the upper nozzle and applies the front tension force F_T during airfoil rolling. Its function is to straighten the hot blade as it emmerges from the rolling dies. Forces in the range of 200 to 600 pounds are applied by means of a pneumatic cylinder located behind the upper hydraulic cylinder shown in Figure 18.

The other force applied vertically from the upper side of the machine is the root injection force F_R. This is applied through the center of the upper nozzle and causes the workpiece to upset within the dies thus forming the blade root. The hydraulic system for root injection employs a hydraulic accumulator to maintain peak pressure during ram descent, and a flow control valve to control the velocity of the ram. Forces in the range of 7,000 to 13,000 pounds are used for blade root injection.

The upper and lower nozzles which serve to guide and support the workpiece are shown in Figure 21. The lower nozzle shown in Figure 22 has a simple tool steel ram which applies the tip feed force F_T to the workpiece (see Fig. 20). The upper nozzle is shown disassembled in Figure 23 is more complex. Because of the high compressive forces involved in root injection, the upper ram was designed in the form of an I-section to resist buckling of the 0.25 in. by 0.50 inch extension that pushes against the end of the workpiece. A latching device is incorporated that engaged a notch near the upper end of the workpiece that enables the application of a front tension force F_T during the airfoil roll.

The control system of the machine is described below in Section 3.3.

3.3.2 Tooling

The tooling system for Phase II was designed to overcome a deficiency encountered in Phase I. This deficiency was inadequate airfoil thickness control caused by: (1) displacement of center of die contour from center of die rotation as the result of die refurbishment; (2) inadequate support of the die facings by underlying components; and (3) variation in die gap due to excessive thermal and elastic strains in the forging machine.

Displacement of the centers of contour and rotation now is prevented through use of precision spacers between the die and the die attachments that restore the original die radius for each subsequent refurbishment. The die facings are supported by molybdenum instead of steel, and the process is performed now on a special machine designed for isothermal roll forging of blades where rolling gap stops are provided for closer control of the die gap.

Figure 21.

Feeder Nozzles for Isothermal Roll Forging of T55 Blade (#78-4277)

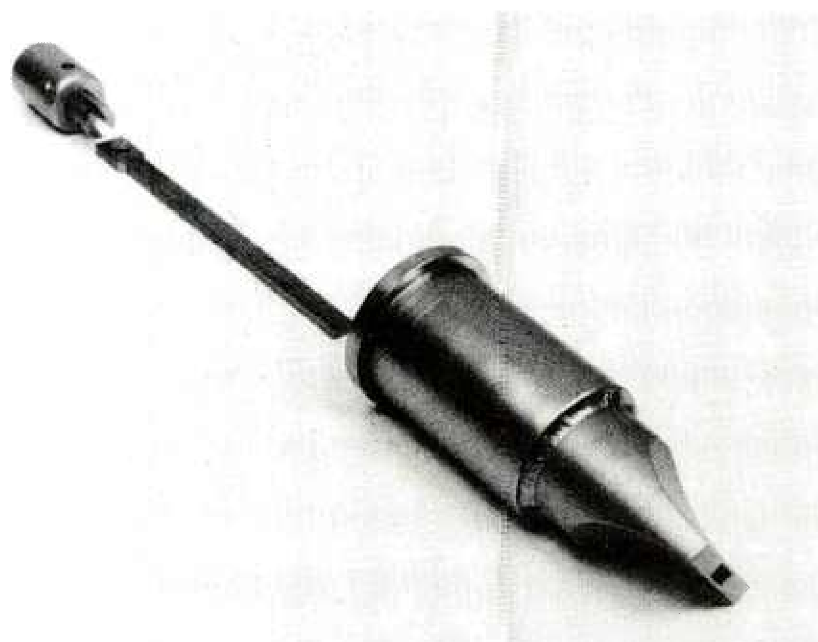


Figure 22. Exploded View of Tip Feeder Nozzle (#78-4279)

Figure 23. Exploded View of Root Injection Feeder Nozzle

The design of the basic die blank is shown in Figure 24. It consists of an outer curved facing of molybdenum alloy braze joined to an unalloyed molybdenum support block. The blade contours are sunk into the outer curved surface, and the opposite flat face mounts onto the forging machine die holder.

The flow diagram for die manufacturing is shown in Figure 25. There are two parallel activities: EDM electrode preparation for die sinking, and fabrication of the die blocks.

For the die faces 0.6 x 2.0-inch MT-104 molybdenum was bent hot using the isothermal shape rolling machine. The supporting block was saw-cut and the O.D. finished turned, and grooves were cut to reduce the surface contact area with the facing thereby increasing heat generation in the facings and decreasing thermal losses to the support block during blade forging. Braze alloy wire (PALCO - the minimum melting composition of palladium and cobalt) was placed in the grooves prior to braze joining at 2300°F in vacuum. After brazing, the mounting face was milled flat, mounting holes drilled, and the outer curved face finish turned. Then die sinking was performed using electric discharge machining.

Figure 26 shows a die set before and after brazing. After machining the mating surfaces between the die facings and the support blocks, the components were hot vapor degreased, etched in 50% nitric acid, de-smutted in concentrated hydrochloric acid, water rinsed and dried. Molybdenum pins and straps were attached, as shown in Figure 26A, to hold the facings

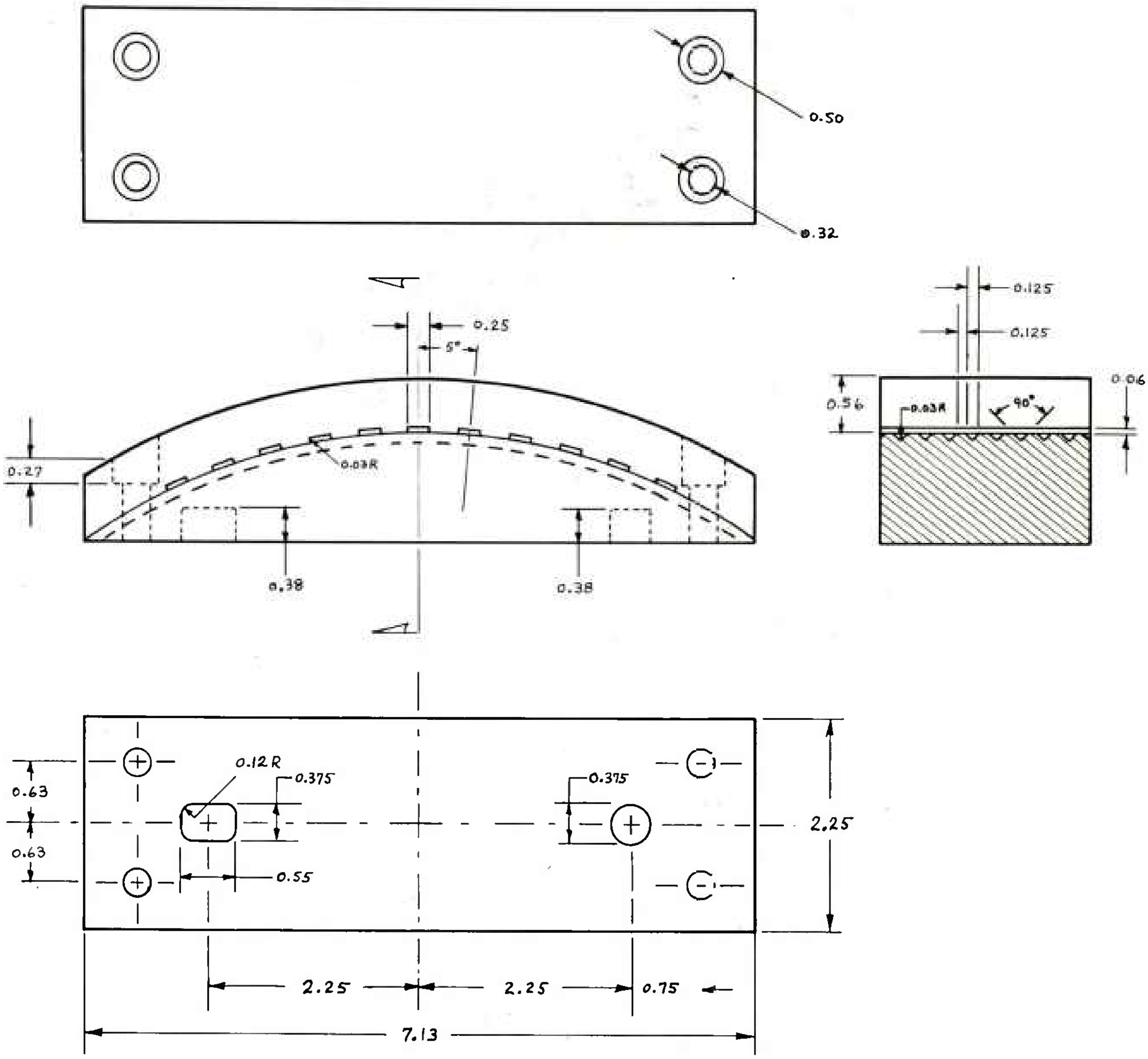


Figure 24. Design of Isothermal Rcll Forge Die Blanks

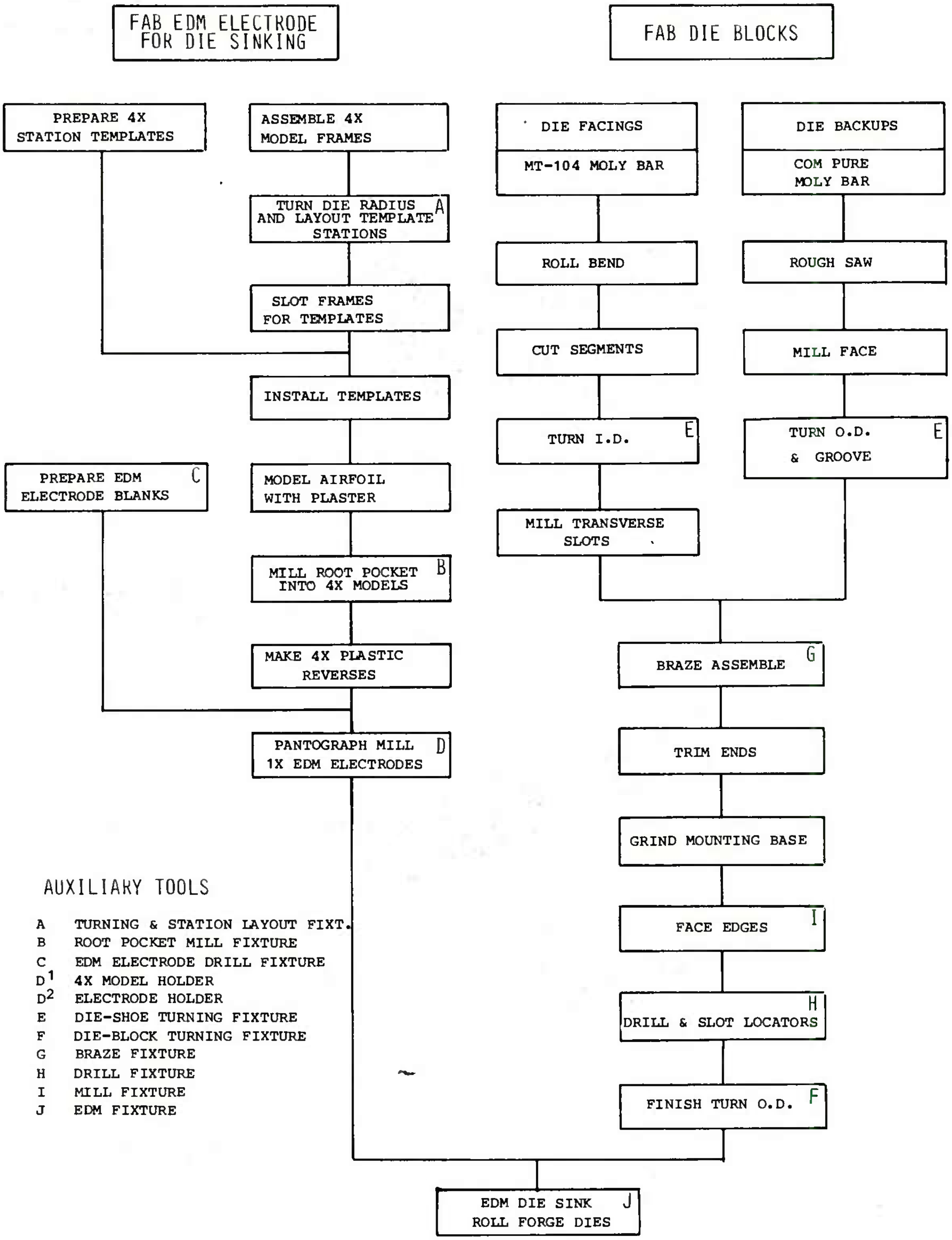
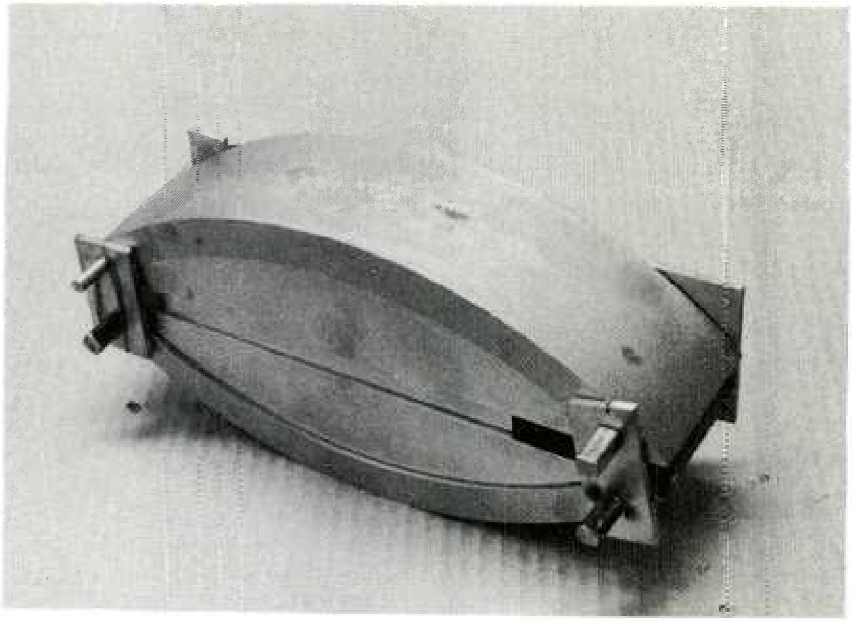
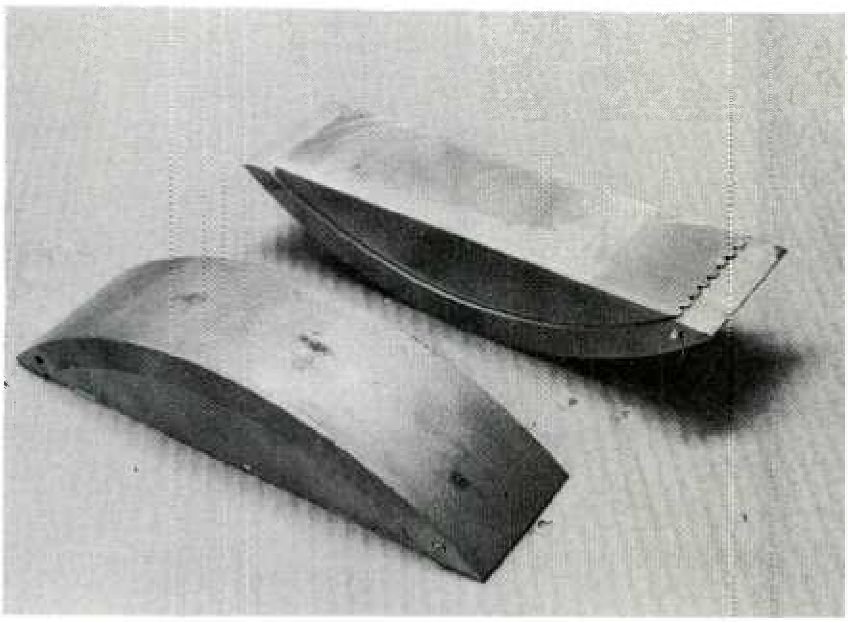


Figure 25. Flow Chart for Roll-Forge Die Fabrication



A. Fixtured for
Brazing (#78-2241)



B. As-Brazed Condition
(#78-2240

Figure 26. Composite Blanks for Blade Forge Die Set No. 1

tightly against the support blocks during the brazing cycle. Braze alloy wire was inserted into the grooves between the facings and support blocks. The assembly was brazed in vacuum at 2300°F for 15 minutes at temperature. Good alloy flow and filleting was achieved with the PALCO alloy braze wire (Western Gold and Platinum Co.). Figure 26B shows the two die blocks after brazing and removal of the pins and straps.

The four-times size models of the EDM electrodes developed in Phase I also were used in Phase II, with modification to the flash lands and gutters (described below). The procedure used for model preparation was presented in the Phase I final report.

The models were used in conjunction with a pantograph machine to mill the blade contours into copper-graphite* EDM electrode blocks, as shown in Figure 27. The electrodes were used to sink the blade contours into the surface of the die block by means of electric discharge machining as shown in Figure 28. A finished die set is shown in Figure 29.

The parameters for flash land design are illustrated in Figure 30. These are the width of the flash land W, the flashland support angle ϕ and the depth of the flash gutter h. For the first tooling iteration these parameters were:

W	0.040 inch
ϕ	45 degrees
h	0.050 inch

The left die which forms the concave side of the airfoil is shown installed in the roll forge machine in Figure 31. The members shown on each side of the die are the rolling gap-stops. They are made of hardened tool steel ground to a radius of 6.730 inches. The rolling gap-stops are electrically insulated from the dies. The radial position of the dies is adjusted by means of precision ground spacers (not shown) that set the flash lands of the dies slightly below and concentric to the rolling gap-stops. During tool proofing of the dies, the spacers were adjusted to produce a flash of approximately 0.002 inch in thickness. Figure 31 shows the position of the dies and gap stops in the forging machine. The two star-wheel screws are mechanical stops similar to those used in Phase I to set the angular position of the dies for the root upset position.

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*EDM-C-3, Poco Graphite, Inc.

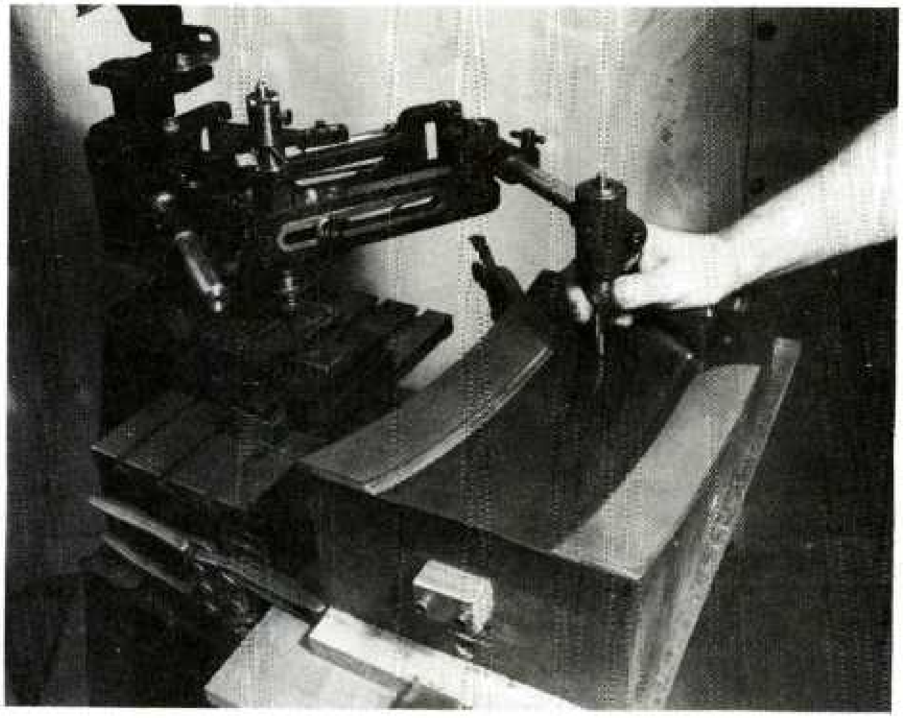

Figure 27. EDM Electrode Preparation on Pantograph Machine (#78-5106)

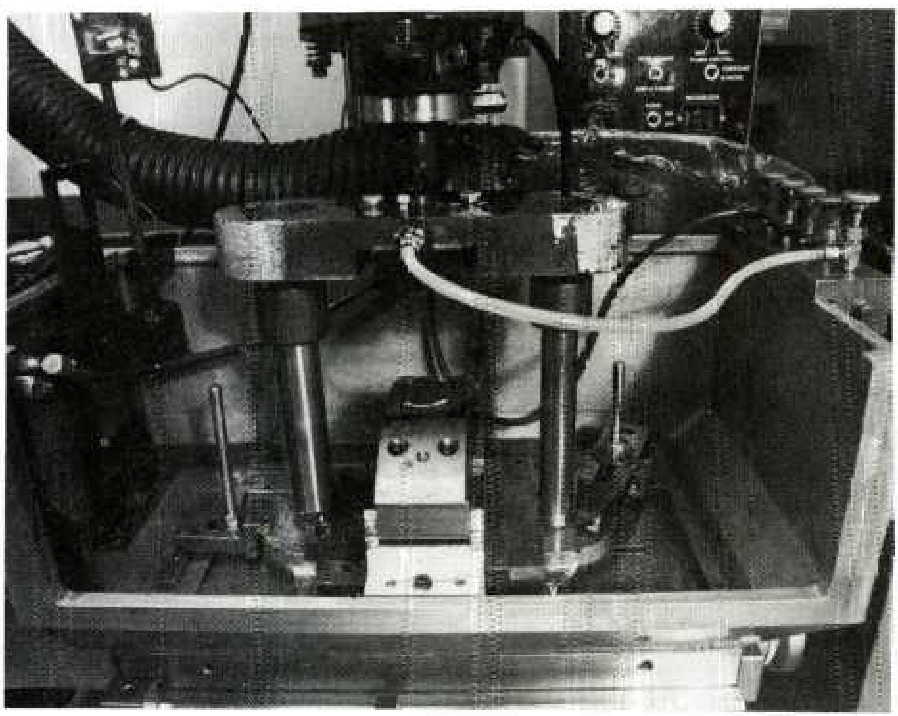

Figure 28. Roll Forge Die Sinking by Electric Discharge Machining (#78-5108)

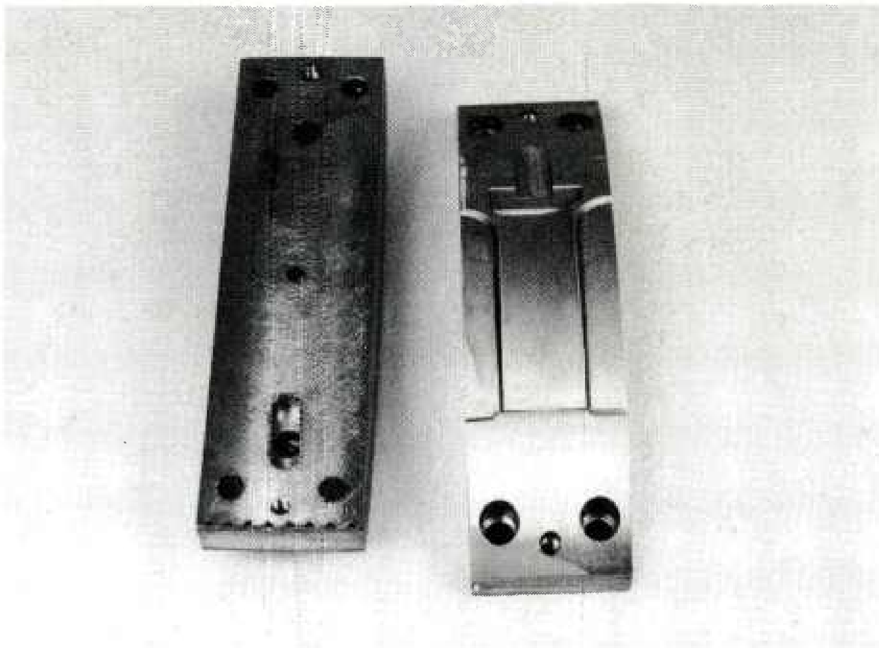

Figure 29. Roll Forge Dies (79-2780)

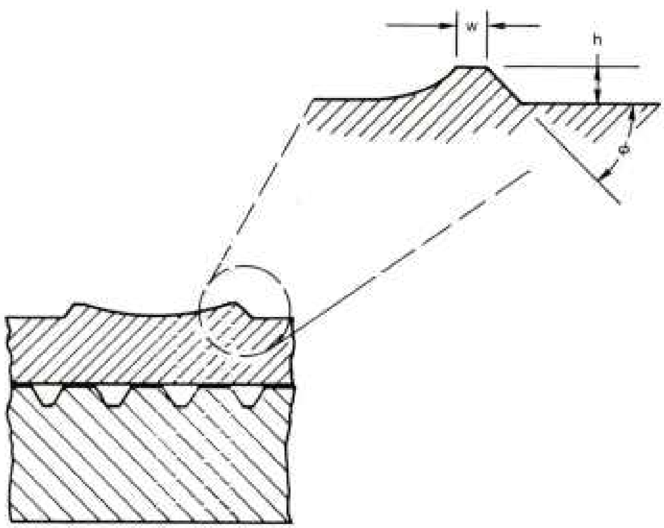

Figure 30. Section Through Roll-Forge Die Showing Flashland Design

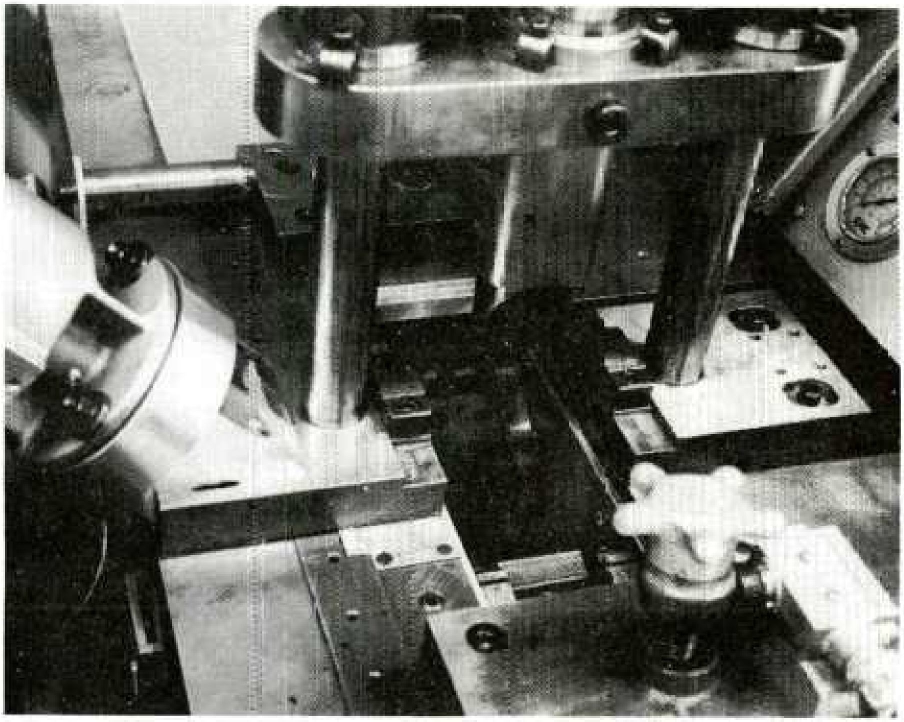

Figure 31. Dies Shown Installed in Roll Forging Machine (#79-5313)

3.3.3 Process Programming and Tool Proofing

The controls of the blade forging machine are shown in Figure 19. Each machine function can be individually controlled by means of the push button panels in the foreground at the right and left of the operator's position. These functions include:

- Die Squeeze - ON/OFF
- Heating Current - ON/OFF
- Tip Feed - Advance/Retract
- Front Tension/Root Injection
- Roll Drive - ON/OFF

The magnitudes of the die squeeze force and heating current are closed loop controlled. Die squeeze by means of a load cell/electrohydraulic servovalve system, and heating current by means of an optical pyrometer/SCR power regulator system. Tip feed force and root injection are manually adjustable by regulating the hydraulic pressure with conventional pressure control valves, and similarly front tension by adjustment of a pneumatic pressure regulator. Roll speed is maintained constant for varying torque conditions by a tachometer feedback/dc motor drive system. Motor speed is adjustable by means

of 10-turn potentiometer control. Conventional electric meters display primary voltage and current, heating current and voltage at the dies, and voltage and current in the drive system. A magnetic pick-up and digital meter displays drive speed, and hydrualic and pneumatic pressure is indicated by conventional pressure gages.

The control console for the forging machine is shown on in Figure 18 (left). This console contains strip chart recorders, analog controllers for die squeeze and heating current, a microprocessor based programmer, numerous relays and potentiometer-type controls. One recorder plots heating current and die squeeze force and the other root injection force and die gap. A typical recording for a blade forge cycle is shown in Figure 32.

The microprocessor shown in Figure 33 is the heart of the control system. It programs two analog channels that control heating current and die squeeze force. In addition, it sequences seven event relays that automatically start or stop the force, current and drive functions which were described above.

The microprocessor has 51 addressable segments each of which is programmable as to time duration, magnitude of each of the two analog channels, and ON/OFF of any combination of the seven event relays. A typical program is shown in Figure 34. Once the program is entered into the programmer memory it can be recorded on magnetic tape, in which form it can be stored for reuse at a future time to reprogram the microprocessor without need to employ the keyboard. Thirty different programs were developed during Phase II during the course of machine check-out and tool proofing. For example, by loading program 1017 into the memory and adjusting hydraulic and pneumatic pressures and rolling speed, a rough roll forged 2nd-stage T55 blade can be made in AM-350. Similarly by loading program 1027 a finish forged blade can be made. With program 1030 the process is close to producing a finish forged blade in a single pass operation.

Calibration curves for heating current, die squeeze force and die rolling speed are shown in Figures 35, 36, and 37. All three are extremely linear, over the range of interest, relative to the setpoint of the current and force programmer/controllers and the digital speed readout.

Tool proofing was initiated with blade forging trials using Ti6Al4V alloy preforms.

Shown in Table 2 are the parametric data for blade root formation and airfoil rolling. The first three trials were made with manual setpoint adjustments to establish the approximate values of heating current and die squeeze force required for root formation with the new roll forging machine. Microprocessor program 1001 was prepared from this data. Three trials with program 1001 produced root fill of approximately 80 percent. Program 1002 imposed a much increased root injection force, however improvement of root fill was not achieved because of the increased time required to achieve the higher force.

The forging cycle was taken to completion in Trials 8 and 9. A completely filled root was achieved with Program 1004 which imposed a higher peak current

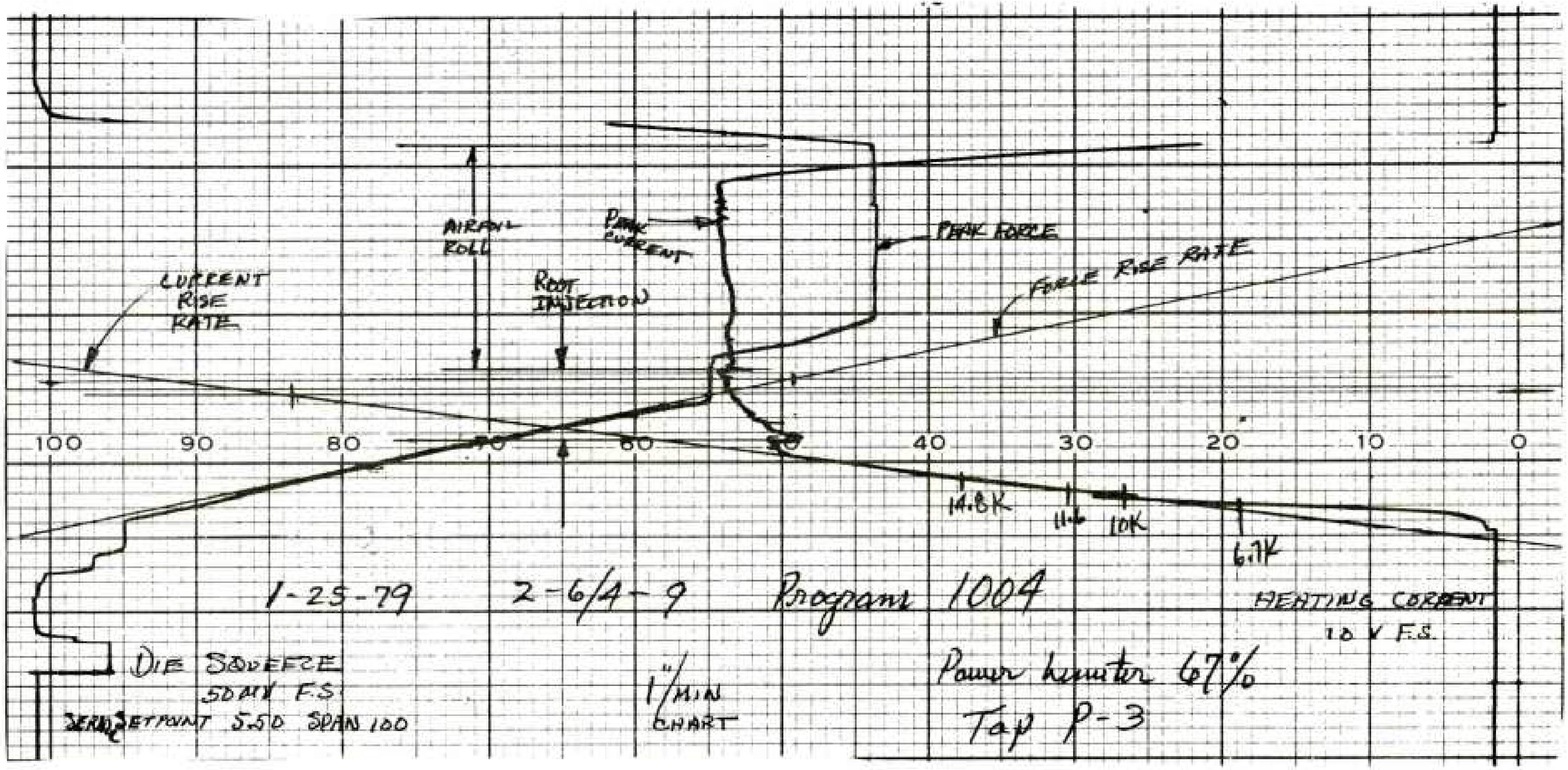

Figure 32. Typical Time Profiles of Die Squeeze and Heating Current for Blade Roll Forging Operation

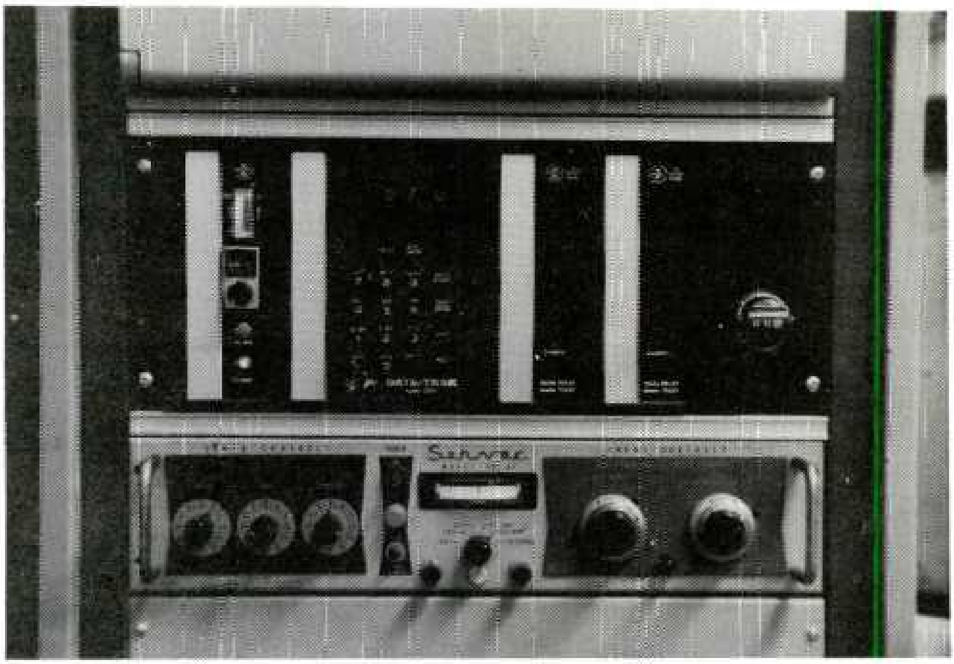

Figure 33. Programmer and Controllers for Blade Forging Machine

and die squeeze than Program 1003 while holding the other parameters essentially constant. The as-forged blades from Trials 8 and 9 are shown in Figure 38.

During airfoil rolling (Trials 8 and 9) it became apparent that a localized protective atmosphere would be required to avoid burn-up of the graphitic forging lubricant* and oxidation of the molybdenum dies. An enclosure was designed and installed that is just large enough to contain the dies and workpiece, and yet provided access for the application of the axial forces.

3.3.4 Production of Test Blades

Tool proofing, in preparation for the first run of test blades, involved the establishment of roll forge parameters, optimizing the program for the microprocessor and forging of some 50 blades in titanium alloy and 12 blades in AM-350. The basic process thus established then was used with minor modifications to produce a first run of 30 test blades in AM-350. The basic parameters established for rough roll forging of the 2nd stage T55 compressor blade were:

- 1900°F workpiece temperature
- 33,000 pounds die squeeze force

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* Sprayon Products Division
Sherwin Williams Company
Anaheim, CA 92806

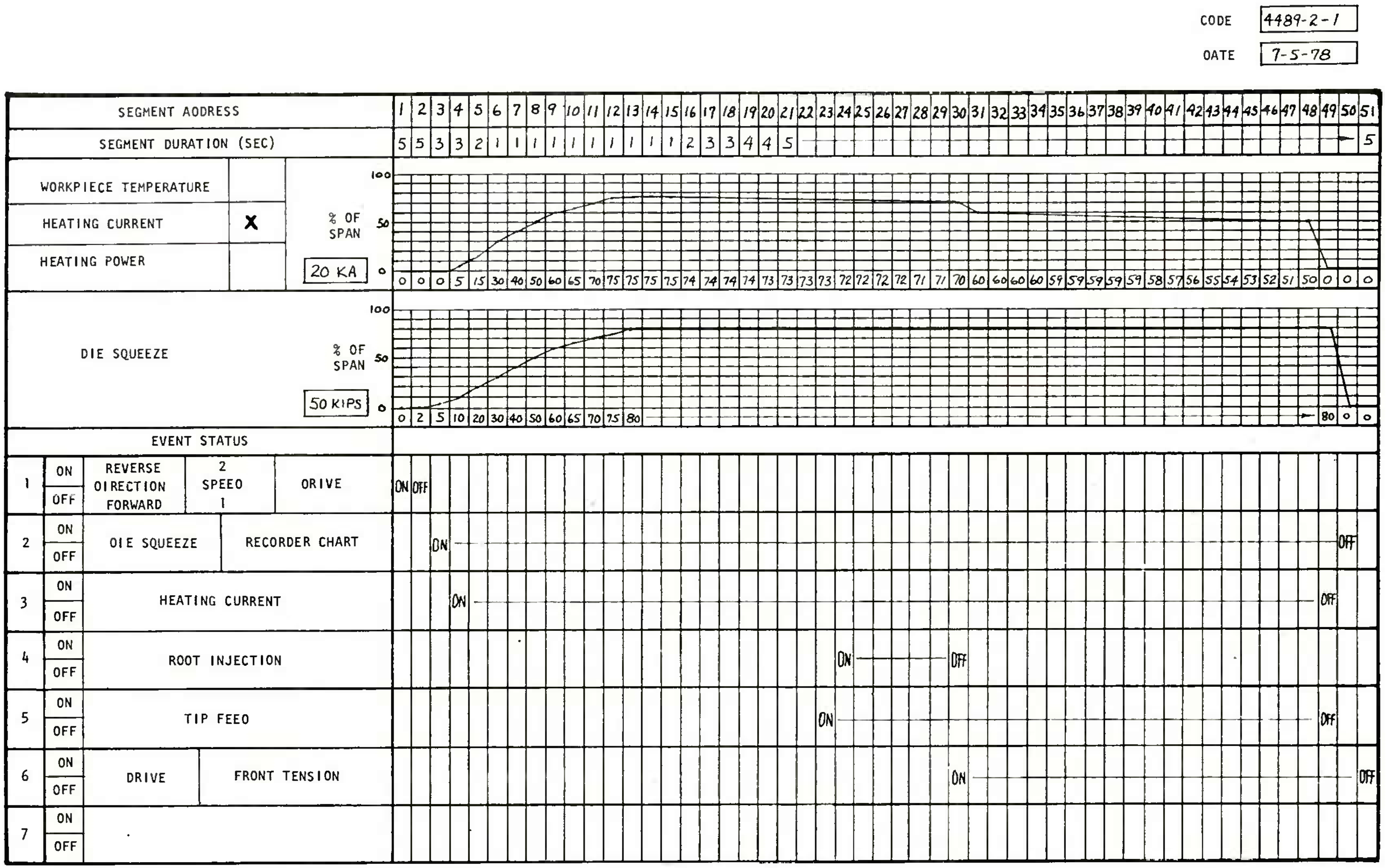


Figure 34. Microprocessor Programming Chart for Isothermal Roll Forging of Compressor Blades

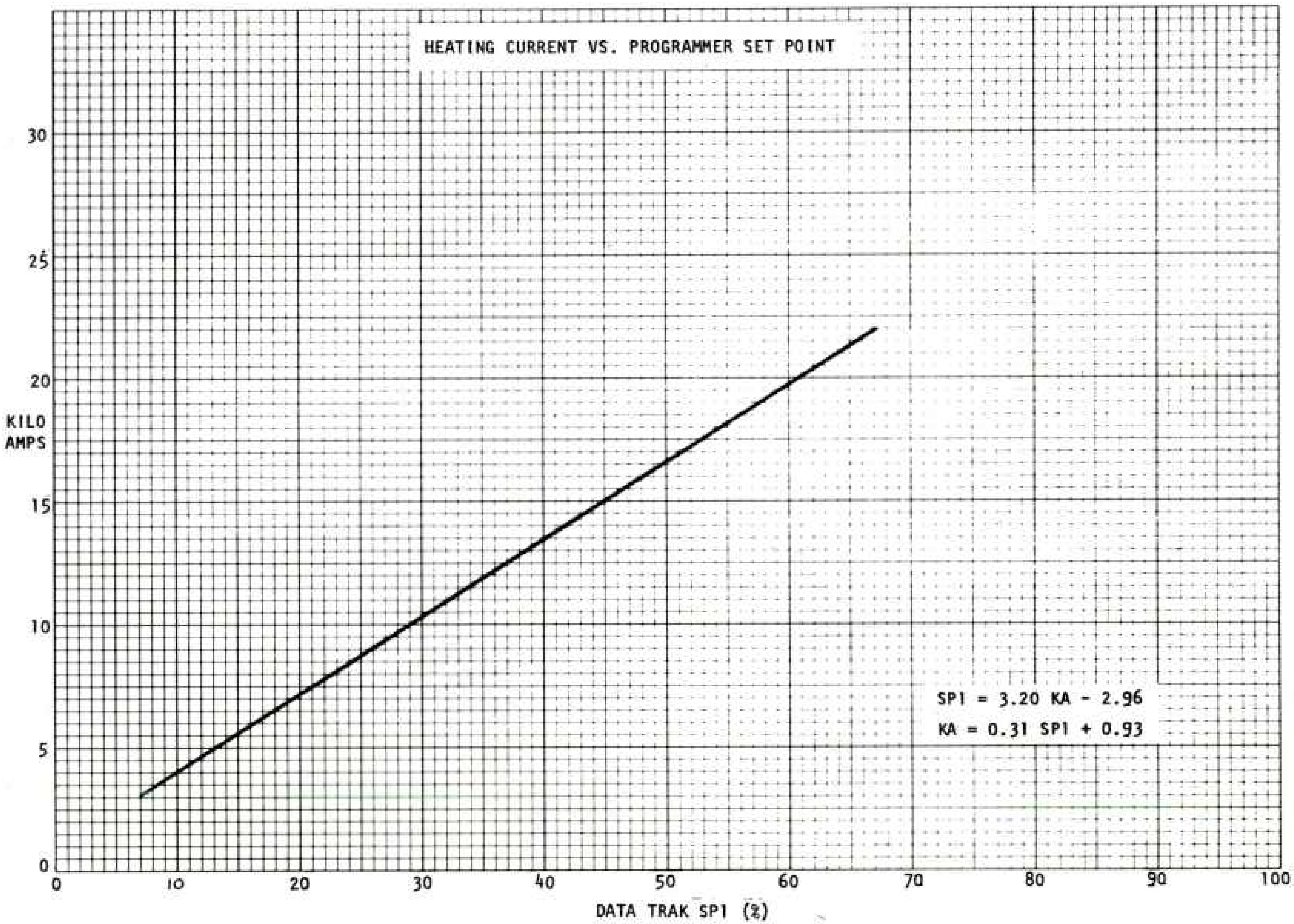


Figure 35. Calibration Curve - Heating Current

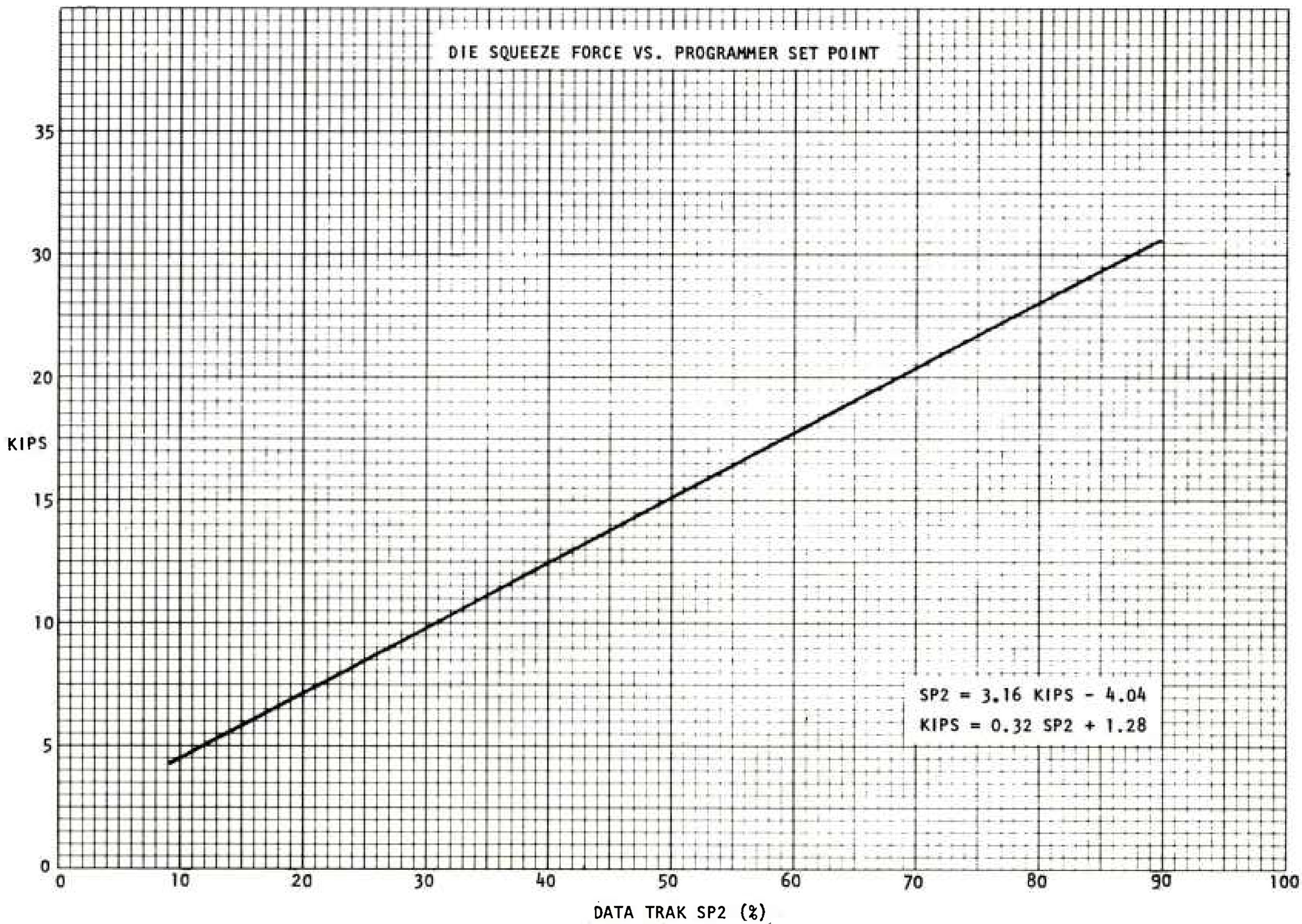


Figure 36. Calibration Curve - Die Squeeze Force

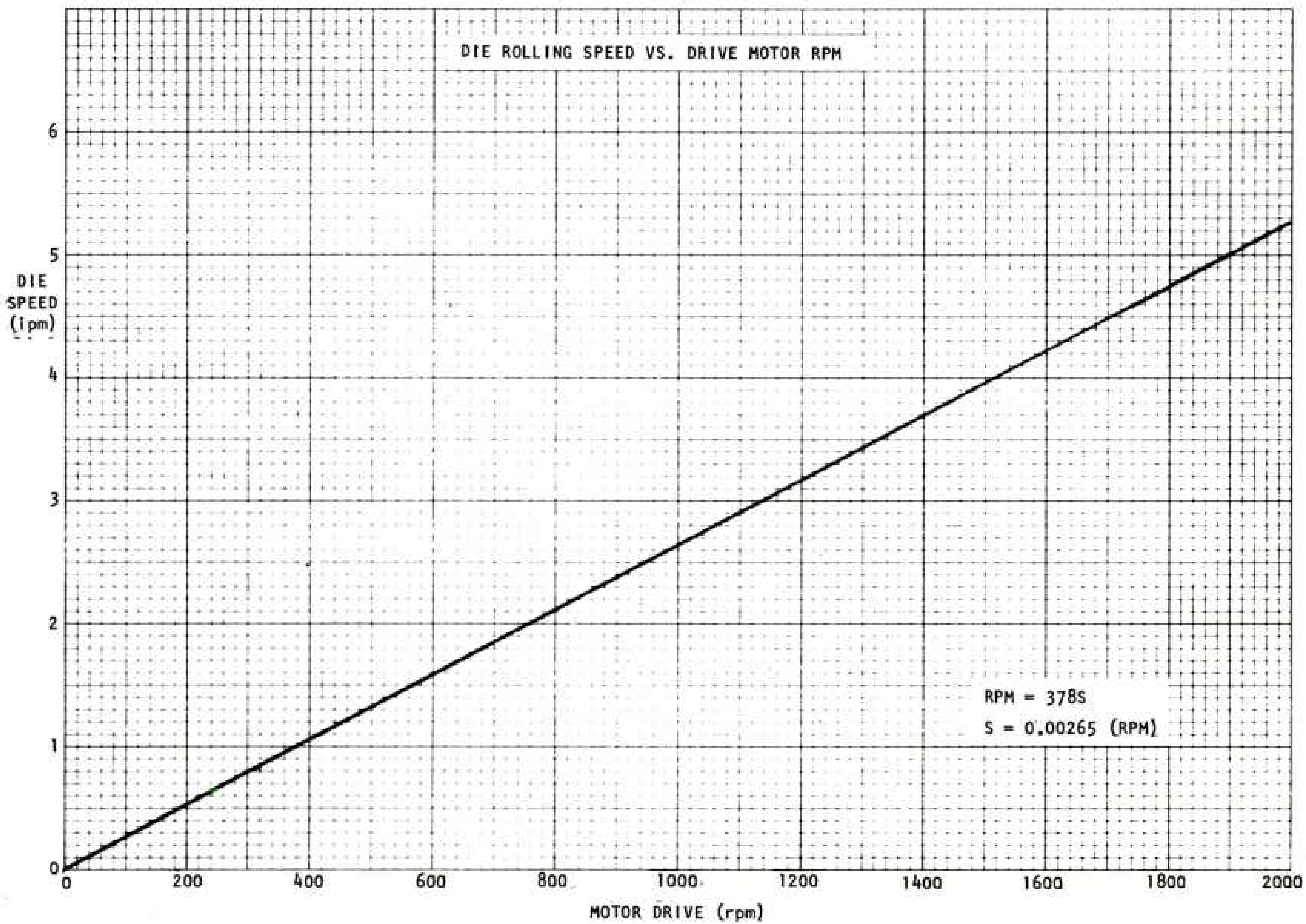


Figure 37. Calibration Curve - Roll Forging Speed

Table 2

Isothermal Roll Forging of T55 2nd Stage Compressor Blades (Initial Tool Proofing Trials)

Blade Code	Micro Processor Program	Heat-Up and Root Formation: Heating Current: Trans. Tap	Heating Current: Limiter (%)	Heating Current: Rise Rate (KA/Sec)	Heating Current: Peak (KA)	Die Squeeze: Rise Rate (KIPS/Sec)	Die Squeeze: Peak (KIPS)	Root Injection: Preset Max Force (KIPS)	Root Injection: Duration (Sec)	Root Injection: Tip Feed (KIPS)	Airfoil Roll: Heating Current (KA): Initial	Heating Current (KA): Inter	Heating Current (KA): Final (10 Sec From Off)	Die Squeeze (KIPS): Initial	Die Squeeze (KIPS): Inter.	Die Squeeze (KIPS): Final (10 Sec From Off)	Front Tension (KIPS)	Roll: Speed (ipm)	Roll: Duration (Sec)	Observations
2-6/4-1	Manual	P1	67	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Run aborted
-2	Manual	P1	67	0.25	16.6	0.51	23.9	9.9	76	2.5	-	-	-	-	-	-		-	-	Approx. 1600°F Poor root fill (15%)
-3	Manual	P1	67	0.80	19.2	0.49	24.0	9.9	73	2.5	-	-	-	-	-	-	-	-	-	Approx. 1700°F Better root fill (60%)
-4	1001	P1	82	0.31	21.3	0.79	23.2	9.9	29	2.5	-	-	-	-	-	-	-	-	-	Approx. 1800°F Good root fill (80%)
-5	1001	P2	67	0.62	19.8	N/A	N/A	9.9	36	2.5	-	-	-	-	-	-	-	-	-	Approx. 1750°F Good root fill (80%)
-6	1001	P2	67	0.59	19.8	N/A	N/A	9.9	46	2.5	-	-	-	-	-	-	-	-	-	Run made to check pyrometry root fill (80%)
-7	1002	P2	67	0.62	19.9	0.45	25.6	30.9	53	1.6	-	-	-	-	-	-	-	-	-	Root fill not improved by higher injection force
-8	[illegible]	[illegible]	67	[illegible]	[illegible]	0.43	25.8	19.8	27	1.6	19.7	19.8	19.0	25.0	25.8	25.8	0.56	1.3	82	Nearly complete root (90%)
-9	1004	P3	67	0.61	21.9	0.47	31.3	19.8	26	1.6	21.6	21.6	16.7	31.3	25.2	31.3	0.56	1.3	91	Complete root fill (100%)
-10	1004	P3	67	0.62	22.5	0.44	33.7	21.6	29	1.6	21.5	22.5	15.7	33.6	33.6	33.4	0.44	1.3	68	
-11	1004	P3	67	0.64	22.6	0.47	33.1	21.6[1]	30	1.6	21.4	22.4	22.5	26.6	33.2	33.1	0.44	1.3	81	
-12	1004	P4	67	0.49	24.6	0.47	33.1	21.6	28	1.6	23.4	24.6	24.0	26.8	33.2	33.1	0.44	1.3	81	
-13	1005	P5	67	0.43	23.2	0.69	33.6	21.6	29	1.6	22.9	22.2	19.8	33.4	33.6	33.6	0.56	1.3	57	
-14	1005	P6	67	0.35	22.0	0.75	33.7	21.6	28	1.3	21.4	21.0	18.4	33.6	33.7	33.7	0.56	1.3	56	
-15	1006[2]	P6	67	0.36	21.3	0.71	33.7	21.6	26	1.3	20.3	20.5	7.8	33.7	33.7	33.7	0.56	1.3	66	
-16	1006[2]	P6	67	0.47	21.1	0.71	33.2	21.6	26	0.94	20.5	19.8	16.2	33.2	33.4	33.4	0.56	1.3	57	Added mechanical stops for root inject position

[1] Actual force achieved after 30 seconds was 13.6 KIPS.
[2] Moved roll start event from segment 22 to 23.

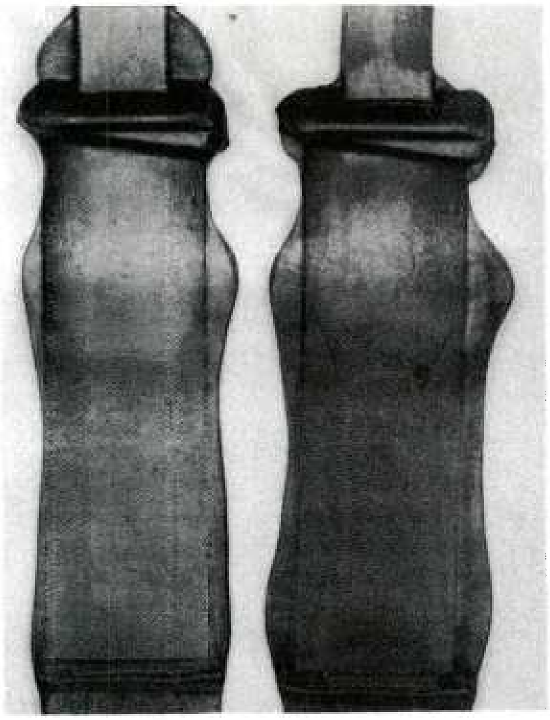


Figure 38.

First Blades Off the New Isothermal Roll Forging Machine (blade codes 2-6/4 -8 & -9, see Table 3)

- 8,500 pounds root injection force
- 1,260 pounds tip feed force
- 220 pounds front tension
- 1.6 inch per minute airfoil rolling speed.

Table 3 summarizes the rough roll forge data for Blade Nos. 12 through 42. The heat-up sequence was varied to a small extent but used the area of parameters established in prior work. Some refinement of these values did occur as a result of these tests.

The principal areas of work were in the root formation and control of t_{max} in airfoil rolling. In general, an injection duration after heat-up of 25 to 28 seconds gave the best results. A rapid rise in injection force as found to be necessary and required installation of a hydraulic accumulator. Typical cycles were a rise rate of 500 to 600 pounds per second to a maximum of 8,500 to 9,200 pounds of injection force.

A tip feed force of 1,260 pounds was used throughout. Current and squeeze force were the principal variables examined in airfoil rolling, conducted at a target temperature of 1900°F. In general, a higher squeeze force tends to reduce the gage (t_{max}) but tends to reduce the surface temperature because the contact resistance is reduced. A squeeze force of 33,000 pounds was adopted together with currents that were reduced along the blade length to maintain a temperature near to 1900°F. A typical temperature recording is shown in Figure 39.

Table 3

Summary of Parameters for Rough Roll Forging T55 2nd Stage Blade in AM-350 Alloy
(Sheet 1 of 3)

BLADE CODE 2-AM-	MIRCO PROCESSOR PROGRAM	HEAT UP					ROOT FORMATION			TIP FEED	AIRFOIL ROLL: HEATING CURRENT KA / DIE SQUEEZE KIPS / OPTICAL TEMPERATURE °F — AIRFOIL STATION						FRONT TENSION	DURATION
		CURRENT		DIE SQUEEZE		DURATION	FORCE		DURATION									
		RISE RATE	PEAK	RISE RATE	PEAK		RISE RATE	PEAK			N	L	J	G	E	C		
		KA/SEC	KA	KIPS/SEC	KIPS	SEC	KIPS/SEC	KIPS	SEC	KIPS							KIPS	SEC
12	1014	0.55	22.3	0.71	33.4	29	0.73	8.64	31	1.26	24.7 33.3 NA	17.0 33.7 –	18.5 33.7 –	18.0 33.7 –	16.0 33.7 –	15.2 33.7 –	0.22	111
14	1014	0.42	23.5	0.72	33.4	26	0.73	8.77	30	1.26	24.0 33.3 1820	19.0 33.8 1830	17.5 33.8 1860	17.6 33.8 1890	15.8 33.8 1875	14.4 33.8 1900	0.22	109
15	1015	0.44	23.6	0.71	33.4	27	0.66	8.64	29	1.26	24.1 33.4 1870	20.0 33.8 1820	19.4 33.8 1880	18.3 33.8 1890	16.6 33.8 1890	14.4 33.8 1885	0.22	110
16	1016	0.62	22.4	0.71	33.4	26	0.72	8.45	41	1.26	22.4 33.3 1895	18 33.7 1880	18.6 33.7 1890	19.0 33.7 1890	17.9 33.7 1890	15.1 33.7 1890	0.22	110
17	1016	0.65	22.4	0.68	33.4	27	0.78	8.38	31	1.26	24.1 33.3 1850	22.2 33.7 1870	20.4 33.7 1930	18.8 33.7 1930	18.0 33.7 1925	15.9 33.7 1920	0.22	110
18	1016	0.53	23.7	0.70	33.4	30	NA	NA	30	1.26	24.0 33.2 1925	19.5 33.6 1920	19.2 33.6 1915	18.8 33.6 1910	18.3 33.6 1910	16.6 33.6 1910	0.22	NA
19	1016	0.55	23.5	0.71	33.2	27	0.75	8.47	27	1.26	24.2 33.2 1840	22.8 33.6 1810	22.5 33.6 1910	18.0 33.6 1920	17.3 33.6 1920	15.8 33.6 1920	0.22	110
20	1016	0.29	22.5	0.71	33.3	26	0.66	8.50	34	1.26	24.3 33.4 1820	21.8 33.7 1895	20.4 33.7 1890	19.9 33.7 1895	18.8 33.7 1890	17.1 33.7 1890	0.22	109
21	1016	0.55	23.8	0.71	33.2	30	0.73	8.39	28	1.26	24.5 33.3 1890	21.0 33.6 1890	21.0 33.6 1890	19.8 33.6 1890	19.6 33.6 1890	17.1 33.6 1890	0.22	112
23	1016	0.73	22.4	0.72	33.3	25	1.46	9.19	29	1.26	24.2 33.3 1860	21 33.6 1900	20.8 33.6 1900	20.2 33.6 1900	18.8 33.6 1900	16.7 33.6 1900	0.28	110

Table 3

Summary of Parameters for Rough Roll Forging T55 2nd Stage Blade in AM-350 Alloy
(Sheet 2 of 3)

BLADE CODE	MIRCO PROCESSOR PROGRAM	HEAT UP					ROOT FORMATION				AIRFOIL ROLL							
		CURRENT		DIE SQUEEZE		DURATION	FORCE		DURATION	TIP FEED	HEATING CURRENT KA DIE SQUEEZE KIPS OPTICAL TEMPERATURE °F AIRFOIL STATION						FRONT TENSION	DURATION
		RISE RATE	PEAK	RISE RATE	PEAK		RISE RATE	PEAK			N	L	J	G	E	C		
2-AM-		KA/SEC	KA	KIPS/SEC	KIPS	SEC	KIPS/SEC	KIPS	SEC	KIPS							KIPS	SEC
24	1016	0.67	23.3	0.72	33.3	26	0.97	9.14	30	1.26	24.1 33.3 1800	21.7 33.6 1900	20.3 33.6 1910	19.7 33.6 1900	18.0 33.6 1900	16.8 33.6 1900	0.33	109
25	1016	0.69	22.7	0.73	33.3	26	0.90	9.26	31	1.26	23.7 33.3 1810	22.0 33.6 1900	20.4 33.6 1910	19.5 33.6 1910	18.4 33.6 1900	16.8 33.6 1890	0.33	111
26	1016	0.84	22.3	0.71	33.3	24	0.94	9.21	25	1.26	23.8 33.3 1800	22.7 41.7 1870	22.9 41.5 1920	21.0 41.5 1900	20.1 41.5 1890	16.3 41.5 1890	0.33	111
27	1016 MOD A	0.49	22.3	0.71	33.3	28	0.78	9.16	21	1.26	24.0 33.3 1770	21.5 33.6 1890	20.5 33.6 1900	20.4 33.6 1900	19.3 33.6 1900	16.8 33.6 1900	0.33	108
28	1016 A	0.69	21.5	0.71	33.3	26	0.78	9.14	28	1.26	24.3 41.0 1790	22.4 43.5 1860	22.6 43.3 1900	21.8 43.3 1900	20.3 43.3 1890	16.0 43.3 1830	0.33	110
29	1016 MOD B	0.63	22.5	0.71	33.3	26	0.80	9.14	29	1.26	24.0 33.3 1840	22.0 33.7 1890	21.3 43.1 1910	20.8 43.1 1900	19.8 43.1 1880	18.7 43.1 1890	0.33	112
30	1016 B	0.63	23.0	0.70	33.3	26	0.99	9.14	26	1.26	24.3 33.3 1780	22.1 33.7 1880	20.9 33.7 1900	19.3 33.7 1890	20.0 41.2 1890	18.8 43.1 1890	0.33	110
31	1016 MOD C	0.62	22.7	0.70	33.5	26	0.78	9.14	26	1.26	24.3 33.5 1800	21.0 33.8 1840	22.6 43.1 1900	20.6 43.1 1900	20.0 43.2 1890	19.6 43.2 1910	0.33	110
32	1016 C	0.51	23.3	0.72	42.1	30	0.35	9.31	18	1.26	23.8 41.8 1830	19.0 38.0 1910	18.5 36.1 1910	19.2 35.7 1910	19.0 35.5 1910	18.1 35.4 1910	0.33	109
33	1016 C	0.49	23.0	0.73	30.3	29	0.46	9.14	21	1.26	24.4 28.1 1810	21.0 28.0 1910	20.1 28.0 1910	18.4 27.7 1910	16.3 27.6 1910	16.5 27.5 1910	0.33	112

Table 3

Summary of Parameters for Rough Roll Forging T55 2nd Stage Blade in AM-350 Alloy
(Sheet 3 of 3)

BLADE CODE 2-AM-	MIRCO PROCESSOR PROGRAM	HEAT UP: CURRENT RISE RATE KA/SEC	HEAT UP: CURRENT PEAK KA	HEAT UP: DIE SQUEEZE RISE RATE KIPS/SEC	HEAT UP: DIE SQUEEZE PEAK KIPS	HEAT UP: DURATION SEC	ROOT FORMATION: FORCE RISE RATE KIPS/SEC	ROOT FORMATION: FORCE PEAK KIPS	ROOT FORMATION: DURATION SEC	TIP FEED KIPS	AIRFOIL ROLL: N	L	J	G	E	C	FRONT TENSION KIPS	DURATION SEC
											HEATING CURRENT KA DIE SQUEEZE KIPS OPTICAL TEMPERATURE °F AIRFOIL STATION							
34	1016 MOD D	0.46	23.0	0.72	35.1	30	0.58	9.11	23	1.26	24.4 35.1 1800	21.2 35.4 1895	21.1 35.3 1900	20.5 35.2 1900	19.7 38.4 1900	18.7 38.4 1900	0.33	110
35	1016D	0.47	22.7	0.73	33.2	29	0.52	9.14	22	1.26	24.4 33.2 NA	20.8 33.5 NA	23.0 33.6 NA	20.9 38.2 1910	19.3 38.3 1890	19.9 38.3 1900	0.33	110
36	1016D	0.48	22.8	0.75	33.2	29	0.44	9.09	19	1.26	24.7 33.3 1810	21.1 33.5 1885	22.2 38.9 1930	20.3 38.9 1920	19.3 38.9 1910	19.4 38.8 1910	0.33	112
37	1016 MOD E	0.47	22.0	0.73	33.2	29	0.58	9.26	22	1.26	24.4 38.7 1770	21.4 39.0 1865	22.6 38.9 1930	21.0 38.9 1920	19.2 38.9 1905	19.9 38.8 1920	0.33	109
38	1016 MOD F	0.65	22.9	0.73	33.5	25	0.77	9.32	28	1.26	24.2 33.5 1800	22.0 33.8 1865	22.8 40.2 1900	20.8 40.2 1890	19.8 40.2 1900	19.2 40.2 1900	0.33	111
39	1016E	0.64	23.0	0.73	39.7	25	0.65	9.14	26	1.26	24.3 39.7 1830	22.5 39.9 1890	22.0 39.7 1900	21.4 39.7 1900	19.8 39.7 1910	19.0 39.6 1900	0.33	112
40	1016E	0.62	23.0	0.73	39.7	32	0.57	9.19	28	1.26	24.3 39.7 1780	22.0 39.9 1890	21.0 39.8 1900	21.3 39.8 1900	20.0 39.8 1900	20.2 39.7 1905	0.33	112
41	1016E	0.67	23.6	0.70	39.8	28	0.52	9.14	27	1.26	24.6 39.8 1860	23.0 39.9 1905	21.7 39.8 1905	20.7 39.8 1905	19.7 39.8 1910	17.7 39.7 1895	0.33	113
42	1016E	0.64	23.3	0.74	39.6	36	0.44	9.11	24	1.26	24.5 39.6 1840	20.5 39.8 1900	20.2 39.8 1895	20.7 39.8 1900	19.8 39.7 1910	18.0 39.6 1890	0.33	112

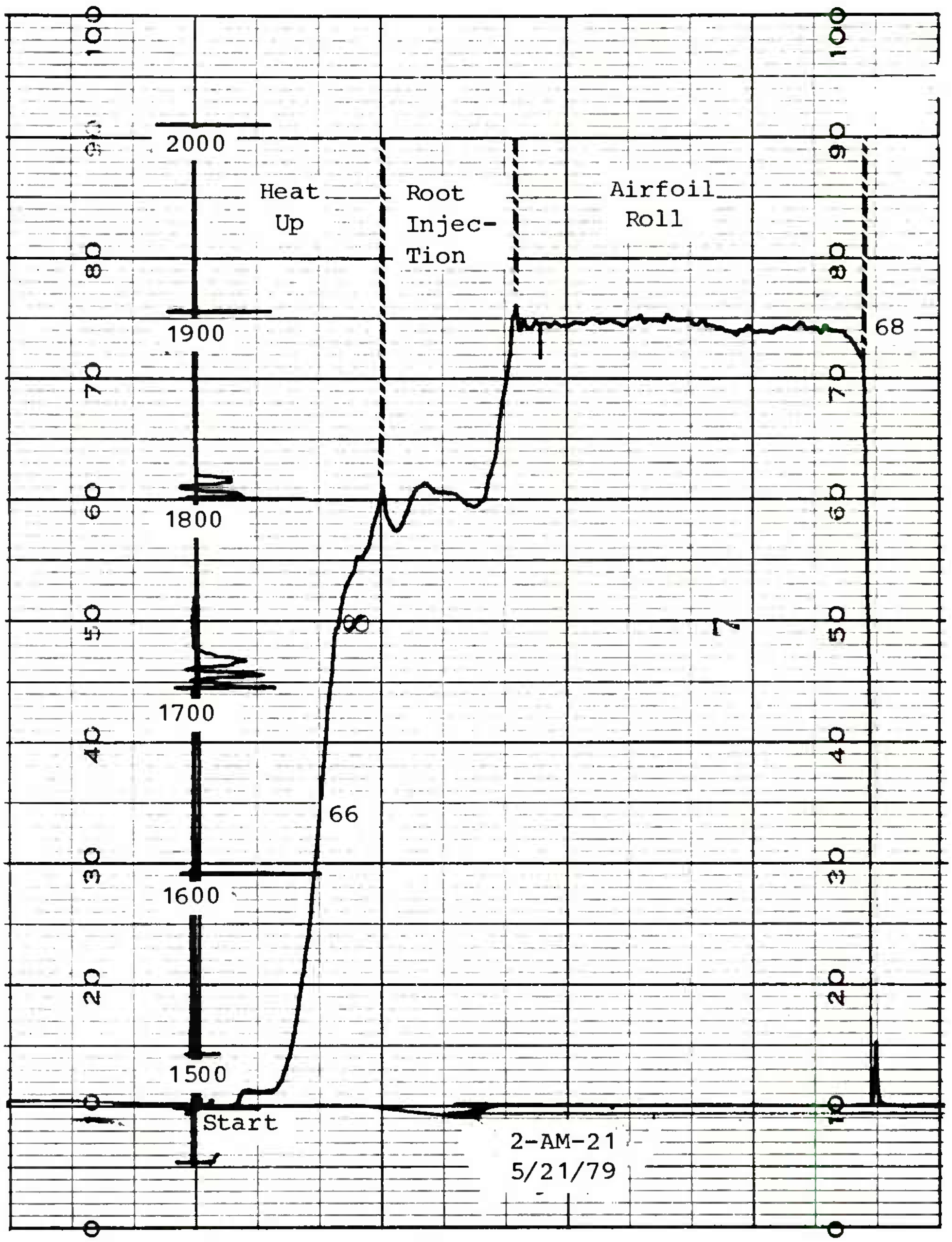


Figure 39. Optical Temperative Feedback Profile During Rough Roll Forge Pass (Blade 2-AM-21)

The front tension was held at 330 pounds for most of these blades.

The final column gives the duration of airfoil rolling, generally 110 seconds (rolling speed 1.6 inch per minute).

Examples of two rough roll forged blades are shown in Figure 40.

Figure 41 shows the fully heat-treated microstructure of a typical rough-forged blade of the production run. The microstructure is considered acceptable as it consists of tempered martensite with discontinuous delta ferrite, and there is no evidence of heavy grain boundary carbides. All surface contamination due to diffusion of the graphitic forging lubricant was removed by electropolishing 0.0005-inch from the surface of the forging. The contaminated surface layer can be seen as a white phase on the as-forged blade shown in Figure 42.

Another parameter evaluated on the rough roll forged blades was airfoil thickness. Table 4a through 4f gives the t_{max} values at the six blade airfoil stations. These show how the range of thicknesses were reduced with changes of parameters to give typical consistencies of ± 0.002 to ± 0.004 inch over the last 10 to 12 blades rolled. (The finished roll forged tolerance is ± 0.004 inch so that these are fully adequate for rough roll forging and demonstrate the possibility of achieving a finished blade with a finish blade with a single pass).

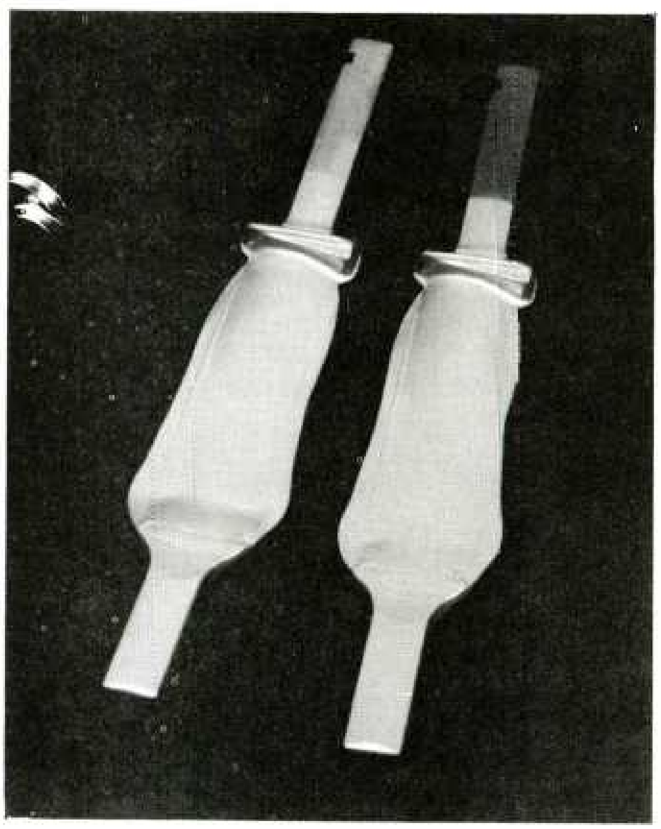


Figure 40. Rough Roll Forged AM-350 Blades

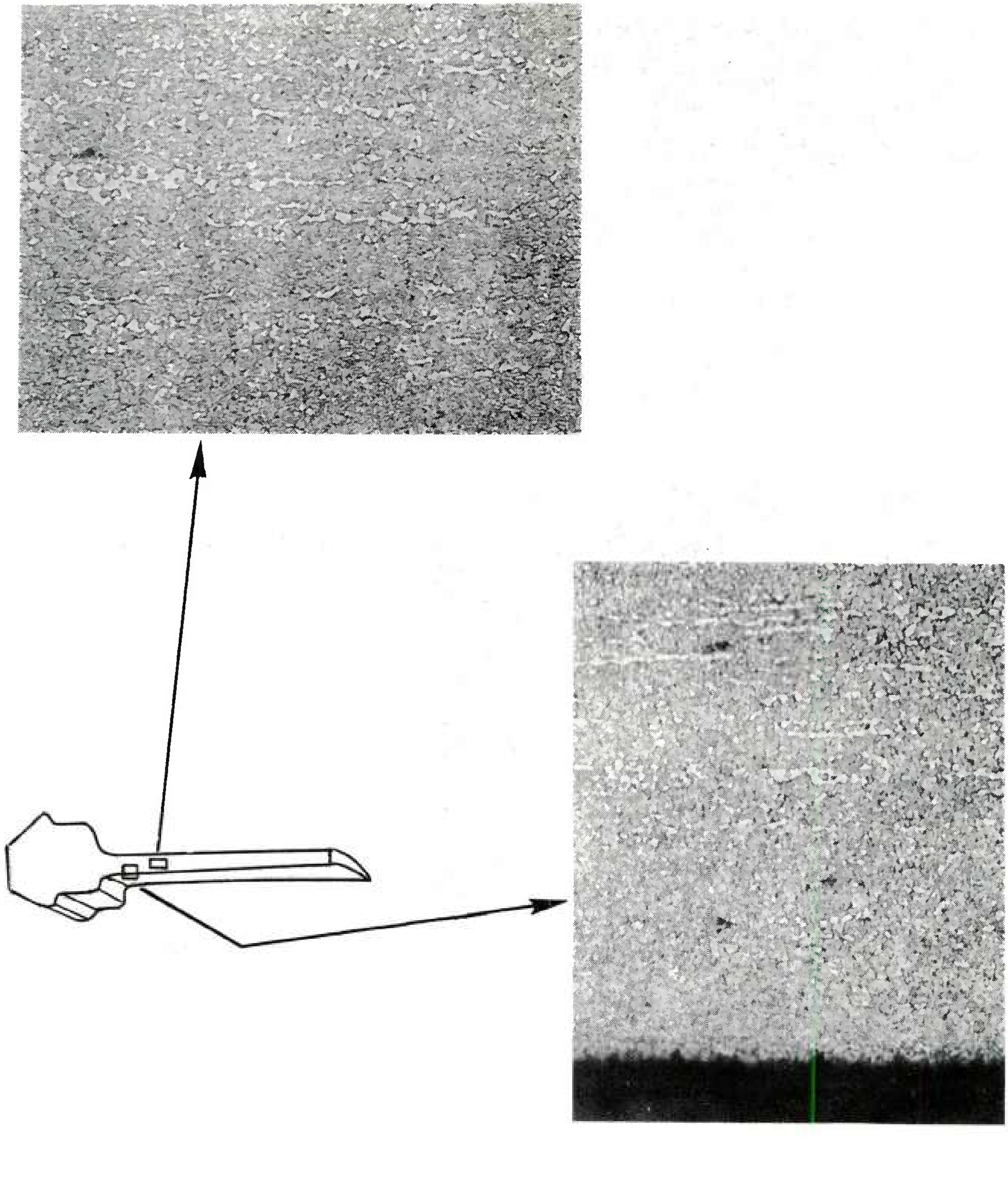
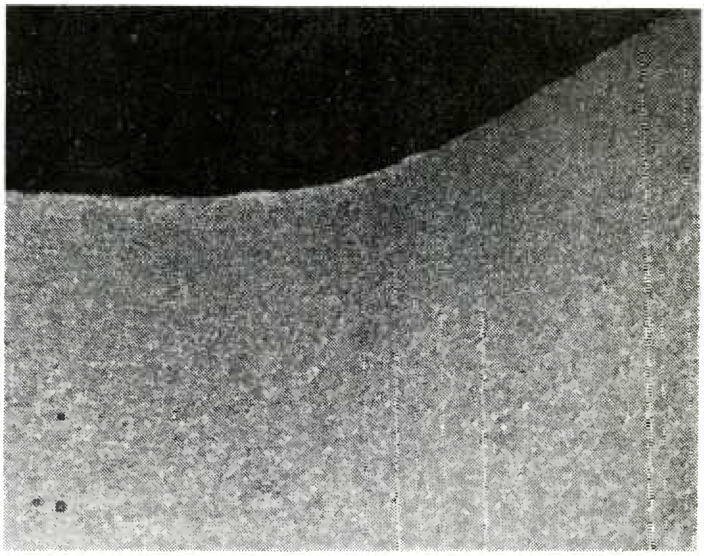
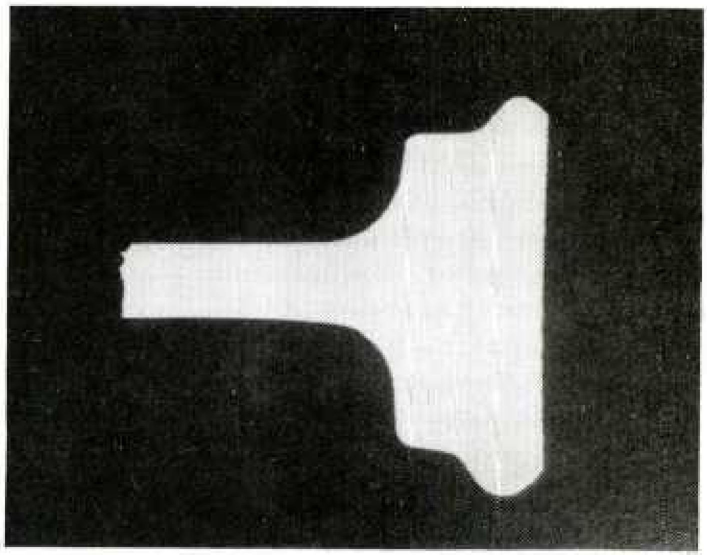


Figure 41. Microstructure of Rough Roll Forged AM-350 Blade (2-AM-31) in Electropolished, Equalized, Overtempered, Hardened, and Tempered Condition. Magnification: 500X



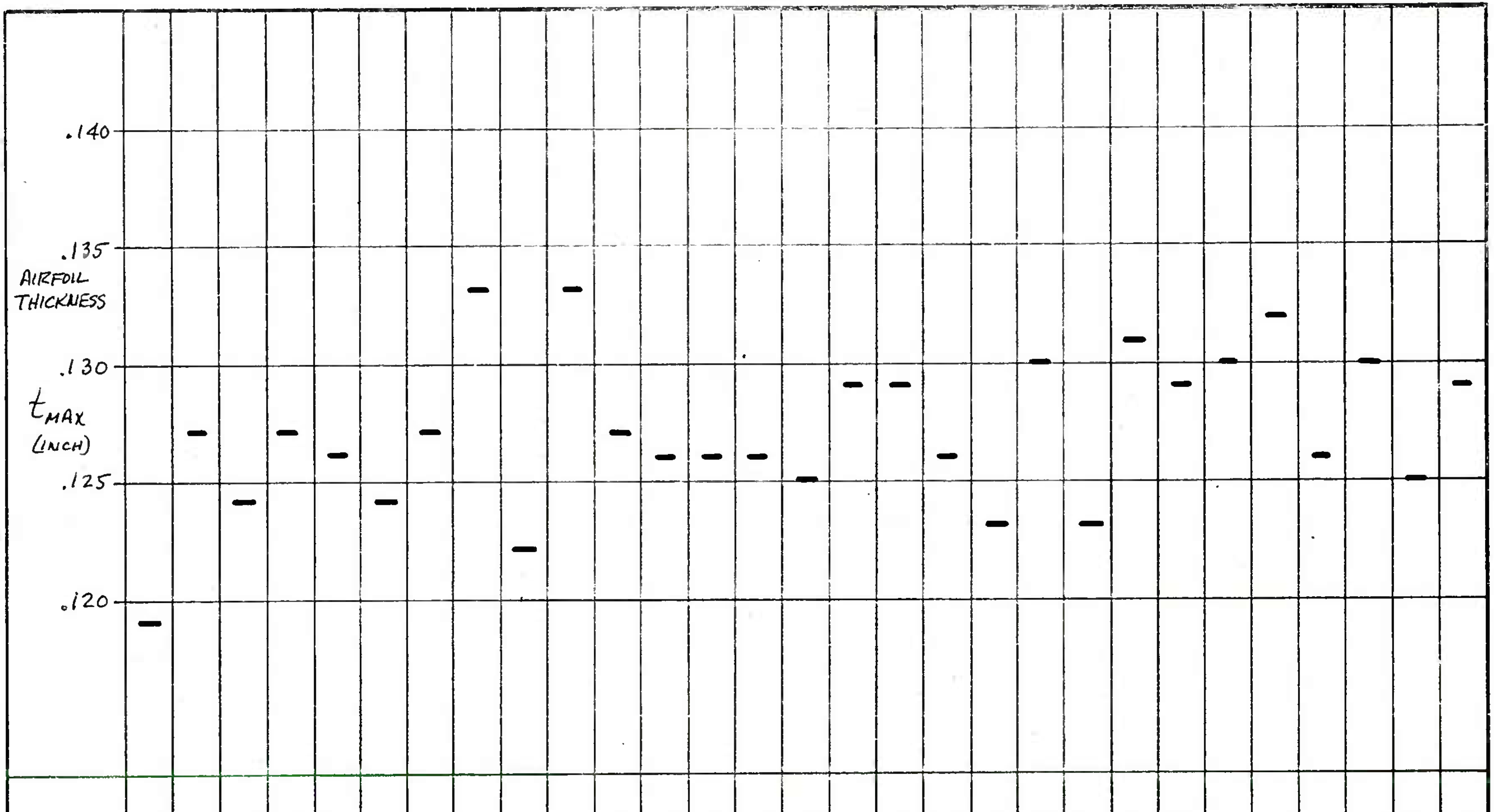
A. Magnification: 50X



B. Magnification: 4X

Figure 42. Microstructure of Rough Roll Forged AM-350 Blade (2-AM-3) As-Forged Condition

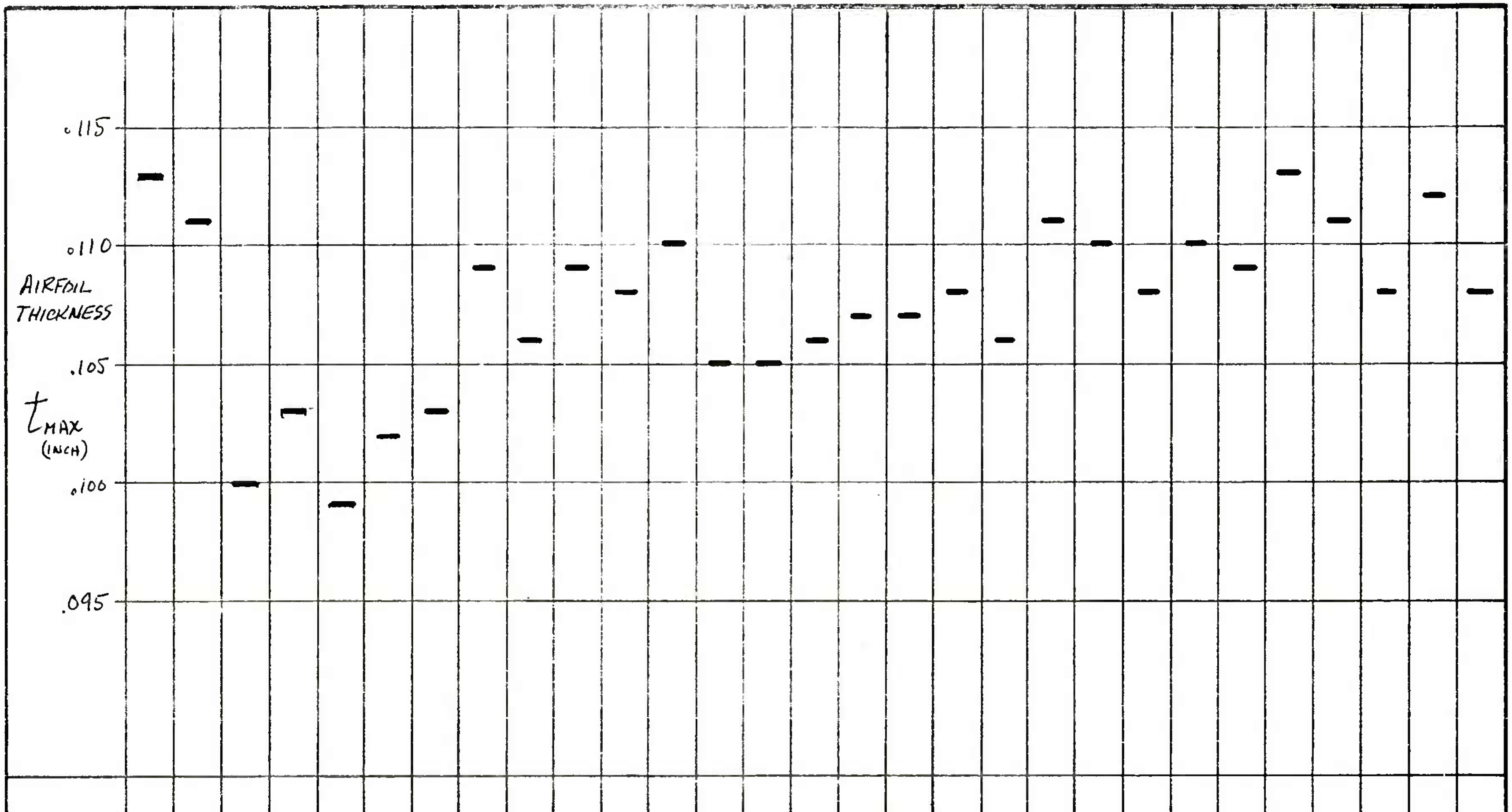
Airfoil Thickness of Rough Roll Forged AM-350 Blades (Station N)
(Sheet 1 of 6)



DIE SQUEEZE (KIPS)	33.3	33.3	33.4	33.3	33.3	33.2	33.2	33.4	33.3	33.3	33.3	33.3	33.3	33.3	41.0	33.3	33.3	33.5	41.8	28.1	35.1	33.2	33.3	38.7	33.5	39.7	39.7	39.8	39.6
HEATING CURRENT (KA)	24.7	24.0	24.1	22.4	24.1	24.0	24.2	24.3	24.5	24.2	24.1	23.7	23.8	24.0	24.3	24.0	24.3	24.3	23.8	24.4	24.4	24.4	24.7	24.4	24.2	24.3	24.3	24.6	24.5
BLADE No.	12	14	15	16	17	18	19	20	21	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42

Table 4

Airfoil Thickness of Rough Roll Forged AM-350 Blades (Station L)
(Sheet 2 of 6)



DIE SQUEEZE (KIPS)	33.7	33.8	33.8	33.7	33.7	33.6	33.6	33.7	33.6	33.6	33.6	33.6	41.7	33.6	43.5	33.7	33.7	33.8	38.0	28.0	35.4	33.5	33.5	39.0	33.8	39.9	39.9	39.9	34.8
HEATING CURRENT (KA)	17.0	19.0	20.0	~18	22.2	19.5	22.8	21.8	21.0	~21	21.7	22.0	22.7	21.5	22.4	22.0	22.1	21.0	19.0	21.0	21.2	20.8	21.1	21.4	22.0	22.5	22.0	23.0	20.5
BLADE No.	12	14	15	16	17	18	19	20	21	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42

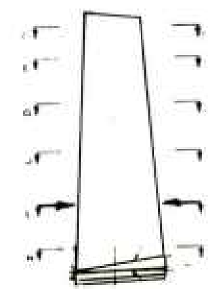
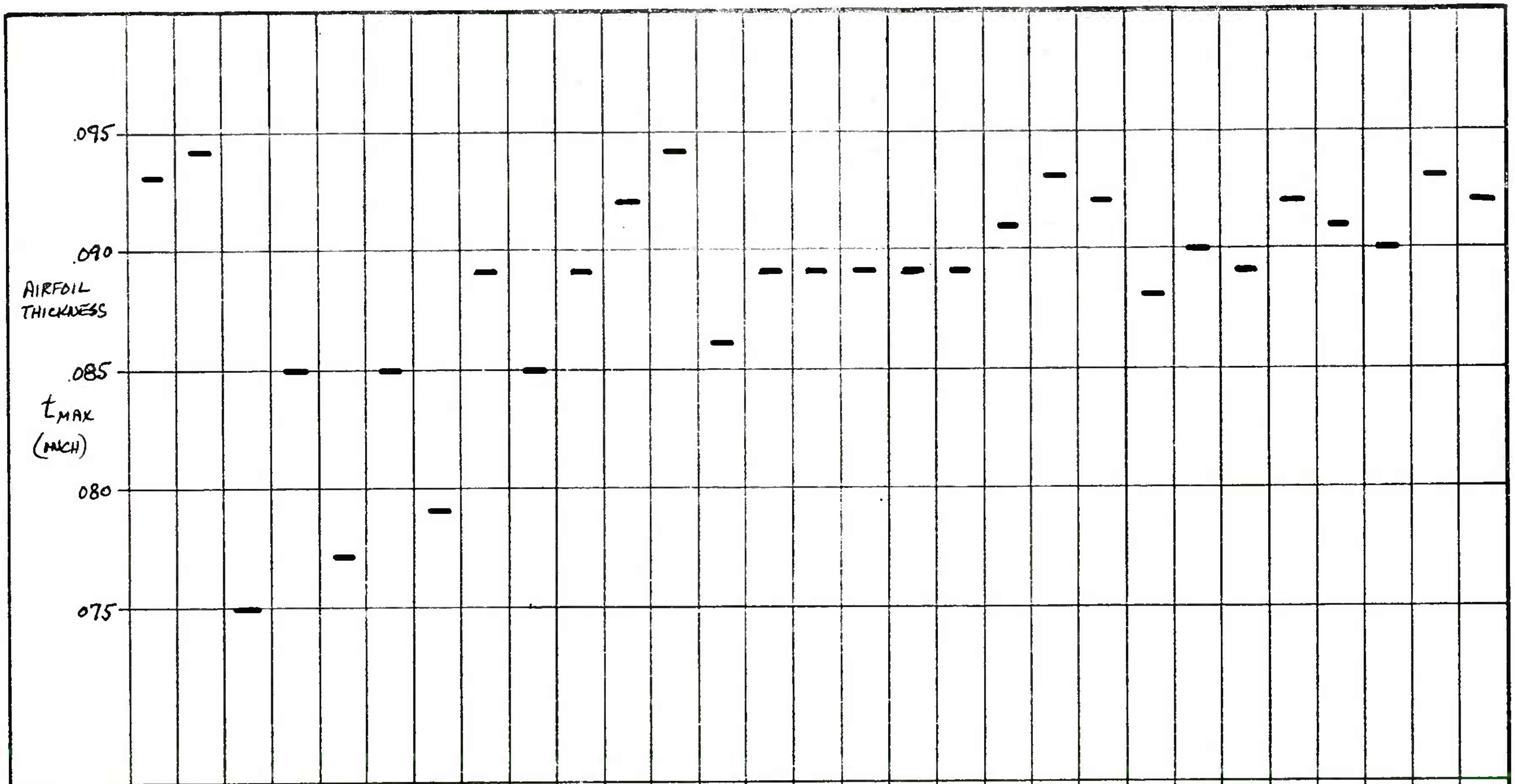


Table [illegible]

Airfoil Thickness of Rough Roll Forged AM-350 Blades (Station J)
(Sheet 3 of 6)



BLADE NO.	12	14	15	16	17	18	19	20	21	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
DIE SQUEEZE (KIPS)	33.7	33.8	33.8	33.7	33.7	33.6	33.6	33.7	33.6	33.6	33.6	33.6	41.5	33.6	43.3	43.1	33.7	43.1	36.1	28.0	35.3	33.6	38.9	38.9	40.2	39.7	39.8	39.8	39.8
HEATING CURRENT (KA)	18.5	17.5	19.4	18.6	20.4	19.2	22.5	20.4	21.0	20.8	20.3	20.4	22.9	20.5	22.6	21.3	20.9	22.6	18.5	20.1	21.1	23.0	22.2	22.6	22.8	22.0	21.0	21.7	20.2

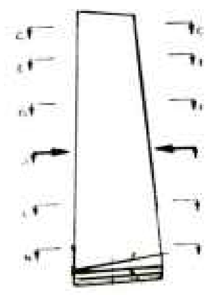
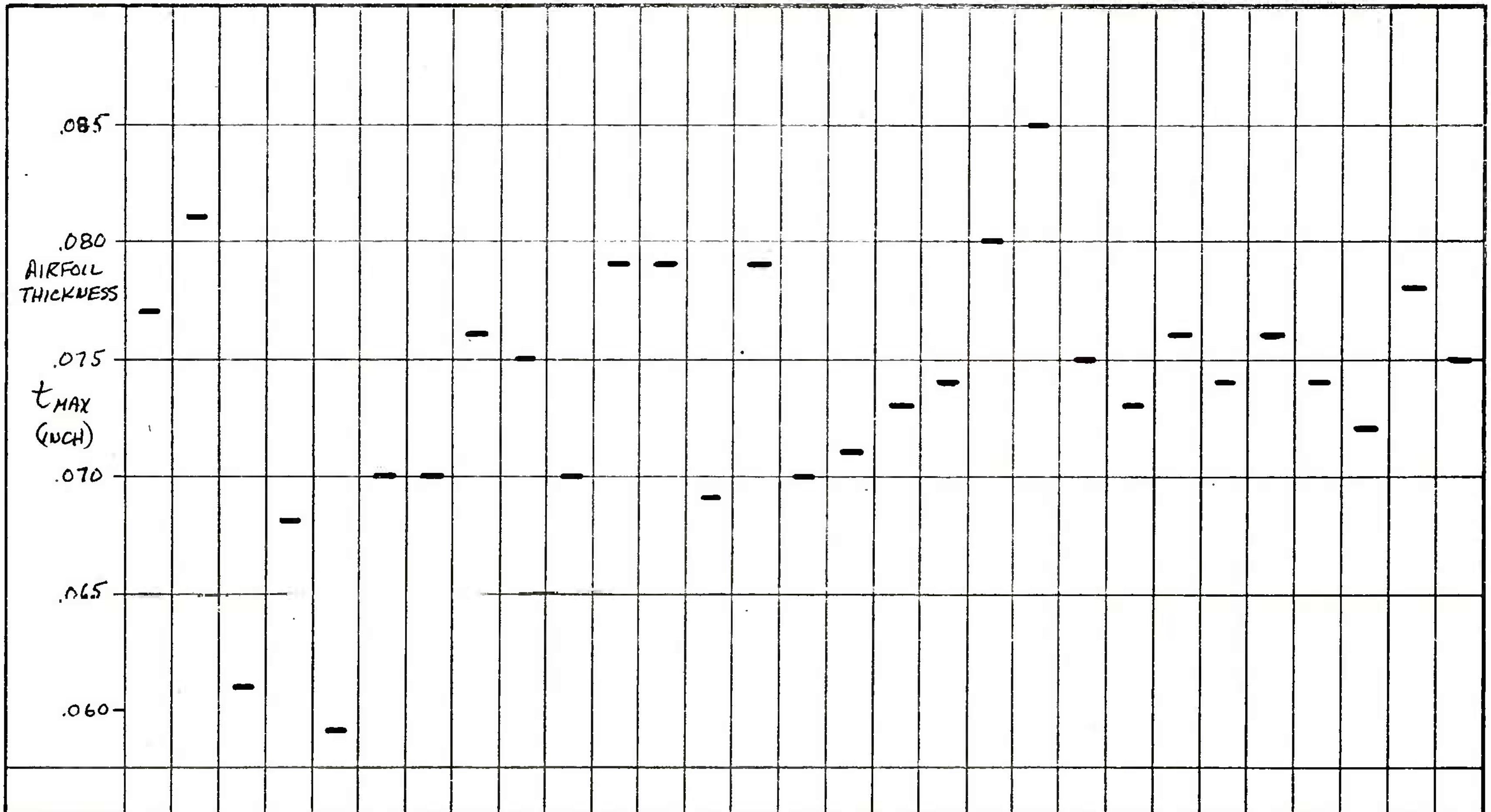


Table 4

Airfoil Thickness of Rough Roll Forged AM-350 Blades (Station G)
(Sheet 4 of 6)



DIE SQUEEZE (KIPS)	33.7	33.8	33.8	33.7	33.7	33.6	33.6	33.7	33.6	33.6	33.6	33.6	41.5	33.6	43.3	43.1	33.7	43.1	35.7	27.7	35.2	38.2	38.9	38.9	40.2	39.7	39.8	39.8	39.8
HEATING CURRENT (KA)	18.0	17.6	18.3	19.0	18.8	18.8	18.0	19.9	19.8	20.2	19.7	19.5	21.0	20.4	21.8	20.8	19.3	20.6	19.2	18.4	20.5	20.9	20.3	21.0	20.8	21.4	21.3	20.7	20.7
BLADE No	12	14	15	16	17	18	19	20	21	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42

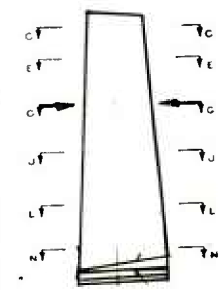
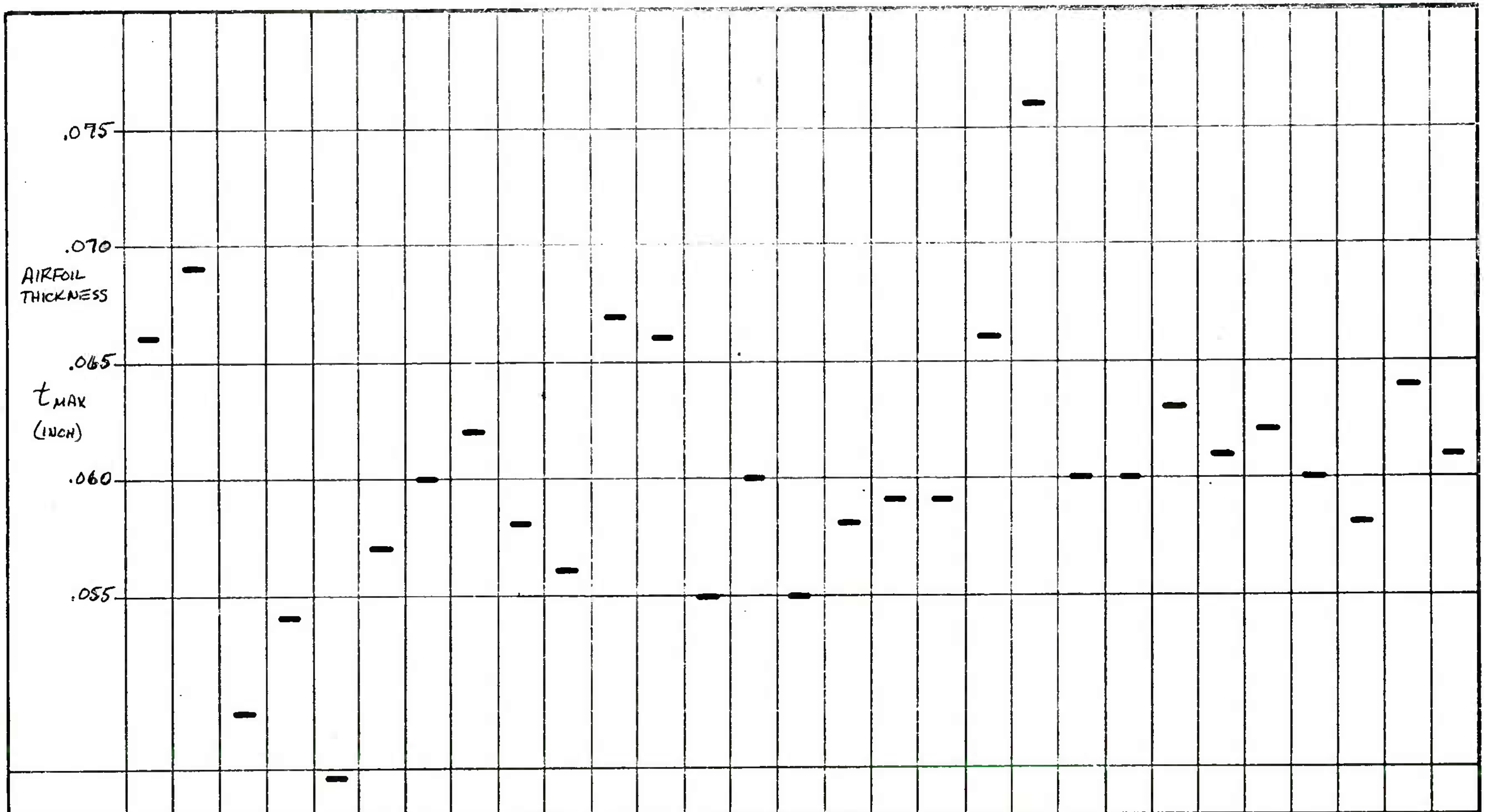


Table 4

Airfoil Thickness of Rough Roll Forged AM-350 Blades (Station E)
(Sheet 5 of 6)



BLADE No.	12	14	15	16	17	18	19	20	21	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
DIE SQUEEZE (KIPS)	33.7	33.8	33.8	33.7	33.7	33.6	33.6	33.7	33.6	33.6	33.6	33.6	41.5	33.6	43.3	43.1	41.2	43.2	35.5	27.6	38.4	38.3	38.9	38.9	40.2	39.7	39.8	39.8	39.7
HEATING CURRENT (KA)	16.0	15.8	16.6	17.9	18.0	18.3	17.3	18.8	19.6	18.8	18.0	18.4	20.1	19.3	20.3	19.8	20.0	20.0	19.0	16.3	19.7	19.3	19.3	19.2	19.8	19.8	20.0	19.7	19.8

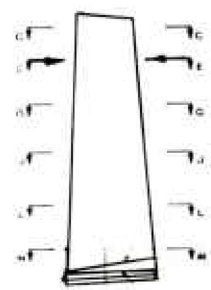
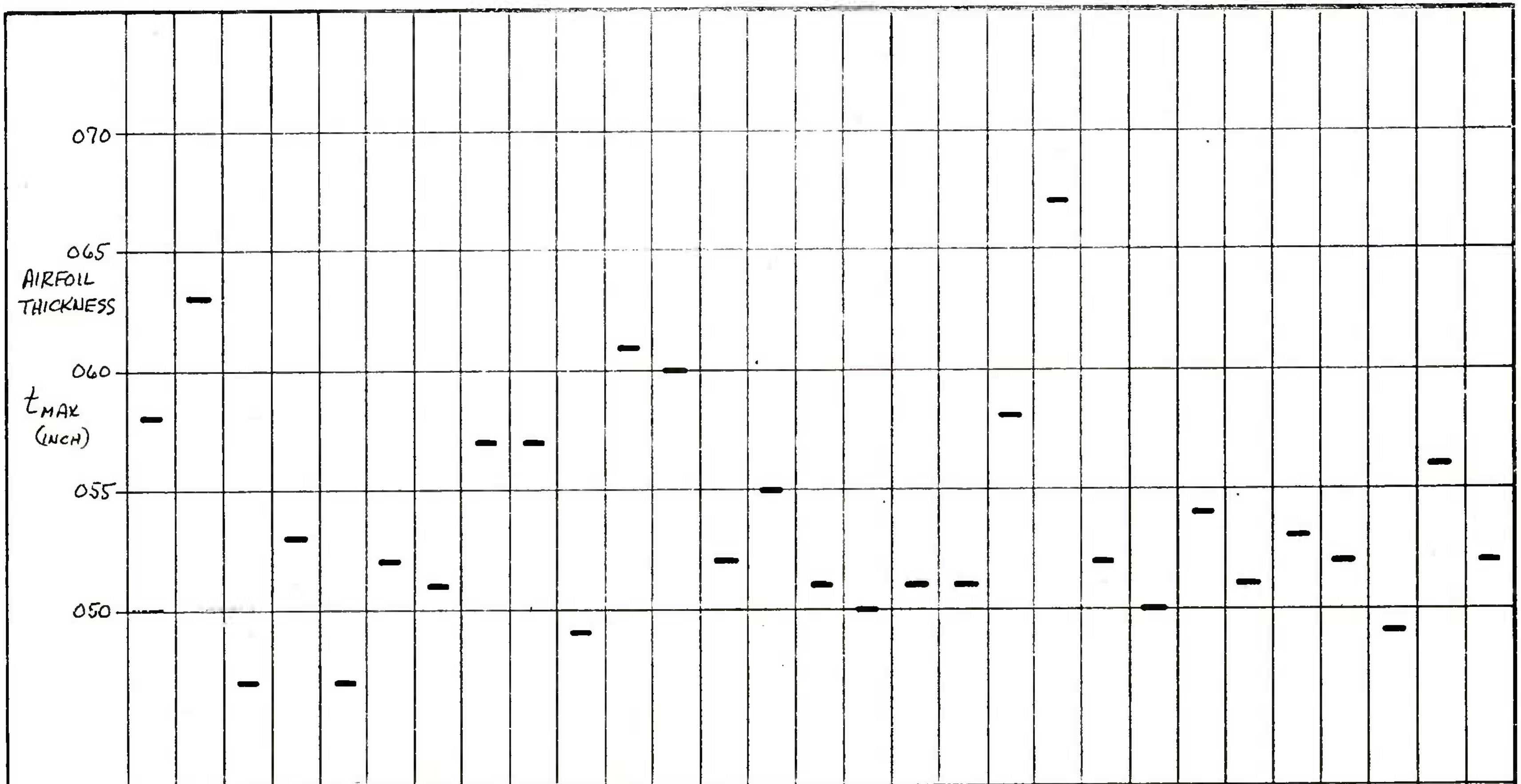


Table 4

Airfoil Thickness of Rough Roll Forged AM-350 Blades (Station C)
(Sheet 6 of 6)



BLADE NO	12	14	15	16	17	18	19	20	21	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
DIE SQUEEZE (KIPS)	33.7	33.8	33.8	33.7	33.7	33.6	33.6	33.7	33.6	33.6	33.6	33.6	41.5	33.6	43.3	43.1	43.1	43.2	35.4	27.5	38.4	38.3	38.8	38.8	40.2	39.6	39.7	39.7	39.6
HEATING CURRENT (KA)	15.2	14.4	14.4	15.1	15.9	16.6	15.8	17.1	17.1	16.7	16.8	16.8	16.3	16.8	16.0	18.7	18.8	19.6	18.1	16.5	18.7	19.9	19.4	19.9	19.2	19.0	20.2	17.7	18.0

Figure 43 presents an analysis of thickness versus heating current for three stations for the last 10 blades. The high thickness values resulted from a squeeze force of 27-28 kips that was inadequate to close the dies. The trend shown with heating current includes these points.

The tensile data are presented in Table 5. Either heat treatment is acceptable to Avco, and both meet the minimum Avco specification.

3.4 TASK 4 - INTERMEDIATE OPERATIONS

The intermediate operations were those that were performed on the rough roll forged blade in preparation for the finish roll force pass. These included trimming of the flash from leading and trailing edges, surface cleaning and reapplication of forging lubricant.

3.4.1 Flash Trim

One trade-off in the use of a simple, constant section preform is that excessive flash is formed at the tip end of the tapered blade airfoil. The excessive flash can be seen in Figure 40. It was observed that trimming of the rough forgings just to chord width produced excessive flash and interfered with airfoil thickness control during the finish roll forge pass, and that trimming to less than chord width eliminated or reduced these problems. The procedure was to trim the flash so as to create a linear taper from full chord width at the root to a lesser value at the tip of the airfoil. Four tapers were evaluated ranging form 0.068 to 0.036 inch per inch. The 0.068 inch taper was excessive, resulting in a finished roll forged blade with inadequate chord near its tip. The 0.036 inch taper was near optimum and produced a full chord with a small amount of flash at each edge. Trimming of both edges was done simultaneously by electric discharge machining with a fixture having two upper electrodes of 0.015-inch thick molybdenum sheet adjustable for different tapers, and a lower platten upon which the forged blade was positioned and clamped. This method was used in Phase II because it provided a quick way to determine the proper taper. It is recommended that a regular blanking die operation be used for high volume production.

3.4.2 Surface Preparation

The surface preparation step between the rough and finish roll forge operation is performed to remove the oxide film that forms during rough roll forging to restore uniform electrical resistivity for the subsequent heating cycle. The processing steps were as follows:

1. Remove graphitic forging lubricant by soaking in hot alkaline solution (Turco 4829LT, 10 oz/gal water, 120-160°F, 20 min)

2. Water rinse and dry

3. Flash trim

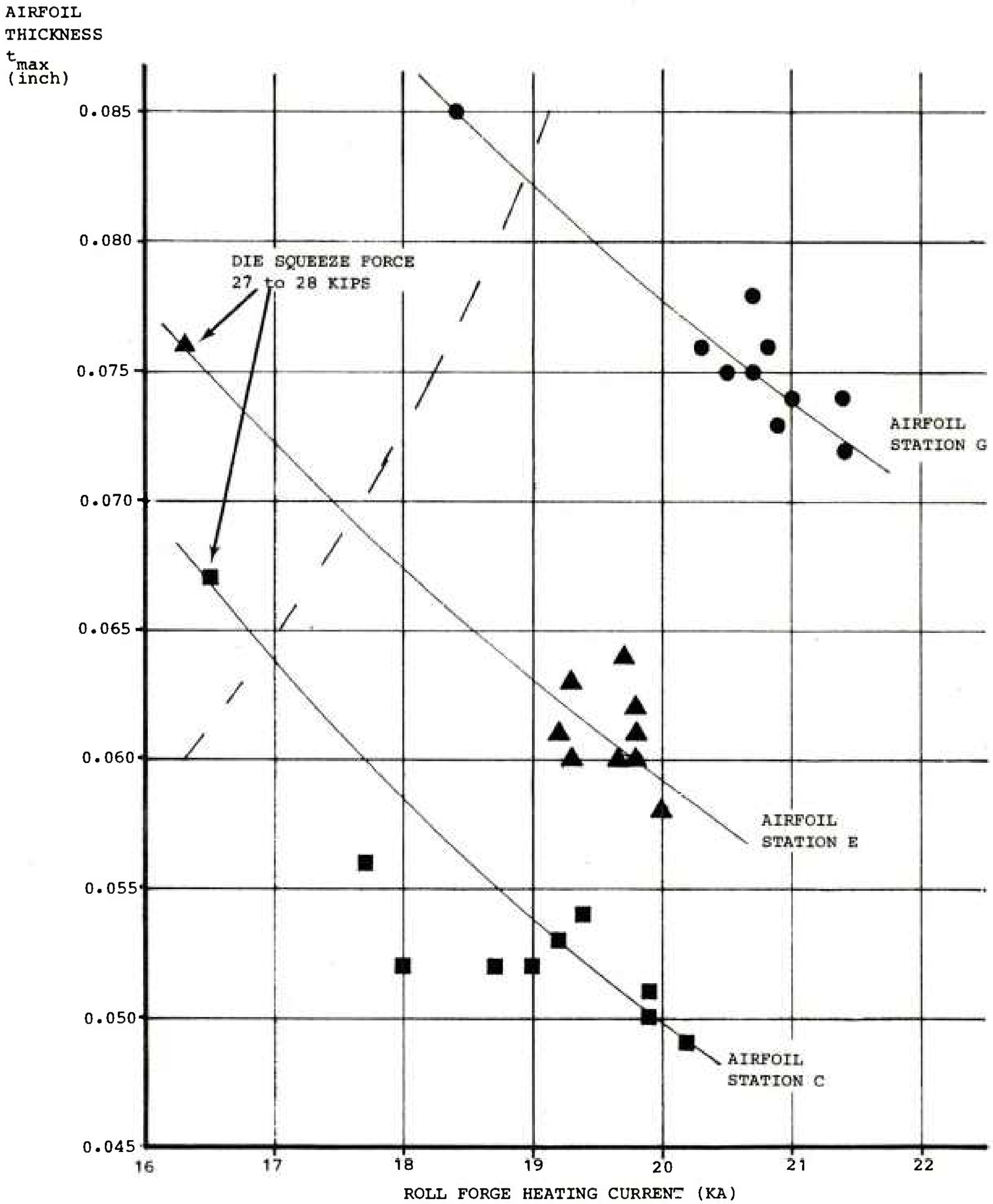
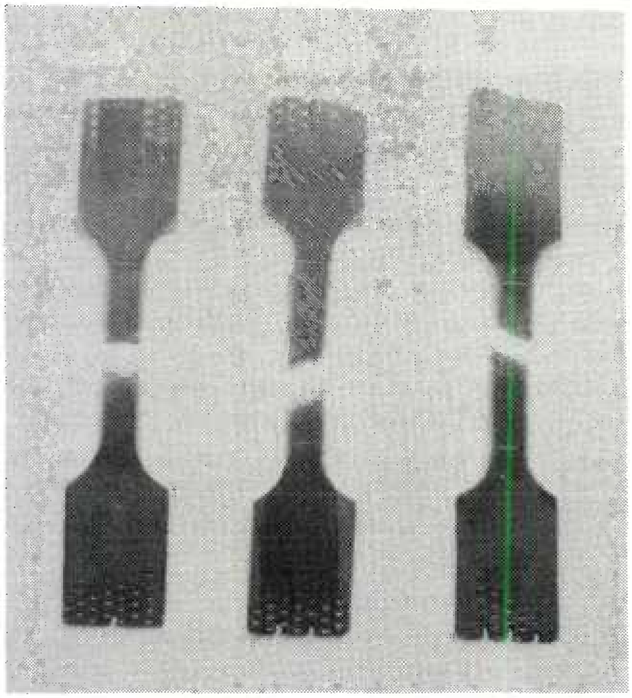


Figure 43. Airfoil Thickness of AM-350 Blades as a Function of Heating Current. Die squeeze force in range 35-40 KIPS except for these points marked.

Table 5

Tensile Properties of Isothermal Roll Forged AM-350 Blades



	Avco Specification Minimum	2-AM-6	2-AM-14	2-AM-24
UTS (ksi)	165	173.2	174.8	173.1
YS (ksi)	140	166.2	156.7	157.6
Elongation (%)	10	14.5	16.0	14.8
Heat Treat Condition	Hardened & 1000°F Tempered	1	2	1

Post Forge Heat Treatment:

1: Harden 1710°F, 15 min + Subzero Cool -100°F, 3 hr + Temper 1000°F, 3 hr

2: Equalize 1425°F, 3 hr + Overtemper 1075°F, 3 hr + Harden 1710°F, 15 min + Subzero Cool -100°F, 3 hr + Temper 1000°F,

4. Hot vapor degrease

5. Remove oxide film with light sandblast (150 mesh garnet at 45 psi)

6. Recoat with graphite lubricant

The graphite lubricant was not applied until just before the finish roll forge operation.

3.5 TASK 5 - FINISH ROLL FORGING

Finish roll forging was performed using the same machine and die design that was used for rough roll forging. The principal changes made for finish roll forging were adjustment of die gap to produce the thinner airfoil, modification of the microprocessor program, and elimination of root injection and tip feed forces. Although two-pass roll forging was used in Phase II, recent experience indicates that a program and preform can be developed that will produce a finish roll forged blade in a single pass.

Adjustment of die gap and modification of the microprocessor program were obvious changes needed for finish forging. Root injection force was eliminated because the root had been made during the rough roll forging operation described above in Section 3.3.3. Blade tip feed was not needed for finish roll forging because the absolute thickness reduction and bite angle were small in comparison with the rough roll forge pass where tip feed was required. The lower nozzle (see Fig. 22) was used solely to guide the blade airfoil as it entered the roll forge dies. Without this guidance the airfoil would tend to skew toward the leading edge because of the greater percentage reduction at the trailing edge in the finish pass.

Table 6 shows the parametric data generated during the establishment of the microprocessor program for the finish roll forge pass using randomly selected blades from the rough roll forge task. The blade code identifies the same blades processed earlier (see Table 3). Table 6 is divided into heat-up and airfoil roll columns. The first 16 blades were forged using 9 program modifications, all involving indirect temperature control through feedback control of heating current. Although this control method produced several blades with dimensions within the tolernace band, it was considered inade quate because of excessive variation in dimensions over the lot of 16. Direct temperature control was introduced with blade No. 5. An optical pyrometer inclined 45 degrees to the long axis of the blade was used to measure the temperature and adjacent to the leading edge as the blade emerged from the roll forge dies. To control temperature, the machine operator adjusted a feedback attenuator control to override the heating current program. This method demonstrated the practicality of closed loop temperature control. It is planned to add this capability to the machine control system in the near future. A typical recording of blade edge temperature is shown in Figure 44. Table 7 shows the mean and standard deviation values of temperature and current at each of the airfoil stations for the 11 blades produced with superimposed temperature control. The relatively large deviation at Station N (root end of airfoil) was caused by the transient condition

Table 6

Summary of Parameters for Finish Roll Forging T55 2nd Stage
Blade of AM-350 Alloy (Listed in order forged)
(Sheet 3 of 3)

Blade Code 2-AM-	Micro-Processor Program	Heat-Up: Current Rise Rate KA/Sec	Heat-Up: Current Peak KA	Heat-Up: Die Squeeze Rise Rate KIPS/Sec	Heat-Up: Die Squeeze Peak KIPS	Heat-Up: Duration Sec	Airfoil Roll: Heat Current (KA) / Die Squeeze (KIPS) / Optical Temperature (°F) — Airfoil Station N	L	J	G	E	C	Airfoil Roll: Front Tension KIPS	Airfoil Roll: Duration Sec	Remarks
12	1026	1.56	22.7	1.06	33.0	46	22	17	16	14	14	14	0.30	119	*
							33	31	24	22	25	28			
							1800	1900	1900	1910	1900	1920			
38	1026	1.53	22.1	1.14	33.0	47	22	18	15	14	10	15	0.30	118	ROOT OVERHEATED CONTROLLER PROBLEM
							33	31	23	22	25	29			
							1800	1900	1900	1800	1800	1890			
42	1027	0.73	21.3	1.11	33.0	53	20	16	16	14	14	14	0.30	118	*
							33	30	22	22	25	29			
							1800	1900	1905	1900	1900	1900			
43	1027	0.95	21.3	1.15	33.0	46	20	14	16	15	15	14	0.30	119	*
							33	31	23	22	25	29			
							1800	1900	1895	1905	1915	1900			
45	1027	0.91	21.9	1.11	33.0	43	21	16	15	15	14	11	0.30	116	
							33	31	23	22	25	29			
							1850	1900	1910	1900	1890	1905			
36	1027	1.47	22.3	1.14	33.0	43	21	16	16	15	15	15	0.30	117	
							33	31	23	22	25	29			
							1850	1900	1900	1900	1900	1895			
34	1027	1.23	22.3	1.11	33.0	44	20	17	15	14	14	14	0.30	117	ROOT OVERHEATED *
							33	31	23	22	25	29			
							1890	1870	1900	1895	1900	1915			

*Fatigue Test Blade

Table 6

Summary of Parameters for Finish Roll Forging T55 2nd Stage Blade of AM-350 Alloy (Listed in order forged)
(Sheet 2 of 3)

Blade Code 2-AM-	Micro-Processor Program	Heat-Up: Current Rise Rate KA/Sec	Heat-Up: Current Peak KA	Heat-Up: Die Squeeze Rise Rate KIPS/Sec	Heat-Up: Die Squeeze Peak KIPS	Heat-Up: Duration Sec	Airfoil Roll: Station N	L	J	G	E	C	Airfoil Roll: Front Tension KIPS	Airfoil Roll: Duration Sec	Remarks
							Heat Current (KA) / Die Squeeze (KIPS) / Optical Temperature (°F)								
39	1025	1.70	23.9	1.07	42.2	47	24	20	19	19	16	16	0.25	120	*
							39	37	35	37	34	42			
							NA								
28	1025	1.92	23.7	1.05	38.8	35	23	20	17	14	14	15	0.25	118	*
							39	38	38	39	39	39			
							NA								
41	1025	0.95	23.3	2.20	38.0	60	23	20	19	17	16	15	0.25	118	
							38	38	38	38	38	38			
							NA								
15	1025	1.92	22.5	1.07	39.2	46	23	21	18	17	16	15	0.25	117	
							39	39	39	39	39	39			
							NA								
40	1025	NA	NA	NA	NA	NA	NA						0.25	118	RECORDER FAILED TO RUN
							NA								
							NA								
4	1026	1.50	22.5	1.13	33.8	45	22	11	11	13	15	16	0.30	119	
							34	31	23	22	26	29			
							NA								
5	1026	1.88	22.8	1.06	33.8	50	22	20	18	15	14	14	0.30	114	1ST TEMP CONTROLLED BLADE *
							34	31	23	22	26	29			
							1800	1890	1885	1950	1890	1900			
9	1026	1.67	22.3	1.06	33.7	46	22	16	16	14	14	14	0.30	117	
							34	32	24	22	25	29			
							1780	1885	1890	1890	1885	1900			
8	1026	1.97	22.4	1.11	33.0	46	22	18	17	15	15	14	0.30	119	*
							33	31	23	22	25	29			
							1800	1900	1845	1900	1900	1905			
10	1026	1.70	22.7	1.01	33.0	44	22	16	16	15	15	14	0.30	119	*
							33	31	24	22	25	29			
							1750	1890	1900	1910	1915	1900			

*Fatigue Test Blade

Table 6

Summary of Parameters for Finish Roll Forging T55 2nd Stage Blade of AM-350 Alloy (Listed in order forged) (Sheet 1 of 3)

Blade Code 2-AM-	Micro-Processor Program	Heat-Up: Current Rise Rate KA/Sec	Heat-Up: Current Peak KA	Heat-Up: Die Squeeze Rise Rate KIPS/Sec	Heat-Up: Die Squeeze Peak KIPS	Heat-Up: Duration Sec	Airfoil Roll: Heat Current (KA) / Die Squeeze (KIPS) / Optical Temperature (°F)	Airfoil Station N	L	J	G	E	C	Front Tension KIPS	Duration Sec	Remarks
2	1018	2.14	15.0	0.74	33.7	48	Heat Current (KA)	14	14	15	10	10	11	0.23	101	
							Die Squeeze (KIPS)	34	34	34	34	34	34			
							Optical Temperature (°F)	NA								
27	1019	1.80	20.5	0.78	33.8	48	Heat Current (KA)	21	18	17	16	16	16	0.23	102	
							Die Squeeze (KIPS)	34	34	34	34	34	34			
							Optical Temperature (°F)	NA								
26	1020	1.60	24.1	1.07	32.0	46	Heat Current (KA)	24	24	23	15	14	14	0.25	115	*
							Die Squeeze (KIPS)	32	32	32	32	32	32			
							Optical Temperature (°F)	NA								
17	1020	0.85	24.2	1.04	44.0	46	Heat Current (KA)	24	24	23	18	14	13	0.25	118	
							Die Squeeze (KIPS)	44	44	32	32	32	32			
							Optical Temperature (°F)	NA								
23	1021	0.90	22.6	1.05	32.2	41	Heat Current (KA)	22	22	22	14	12	12	0.25	104	TOO HOT STA. J
							Die Squeeze (KIPS)	32	29	21	20	23	26			
							Optical Temperature (°F)	NA								
33	1022	2.03	23.3	1.07	32.1	43	Heat Current (KA)	23	17	20	18	13	13	0.25	103	*
							Die Squeeze (KIPS)	32	31	23	20	23	26			
							Optical Temperature (°F)	NA								
32	1023	1.97	22.8	1.05	32.1	47	Heat Current (KA)	23	17	14	14	15	16	0.25	103	
							Die Squeeze (KIPS)	32	30	22	20	23	26			
							Optical Temperature (°F)	NA								
21	1024	2.03	23.2	1.06	39.7	46	Heat Current (KA)	23	17	13	13	14	14	0.25	115	*
							Die Squeeze (KIPS)	40	33	22	20	23	26			
							Optical Temperature (°F)	NA								
7	1025	2.08	22.8	1.07	40.0	46	Heat Current (KA)	22	16	13	12	12	13	0.25	116	ADJUSTED DIE SQUEEZE FOR CONST. DIE GAP
							Die Squeeze (KIPS)	40	38	22	24	24	29			
							Optical Temperature (°F)	NA								
44	1025	1.83	23.1	1.05	33.2	46	Heat Current (KA)	23	17	13	12	13	14	0.25	111	*
							Die Squeeze (KIPS)	33	31	23	22	25	28			
							Optical Temperature (°F)	NA								

*Fatigue Test Blade

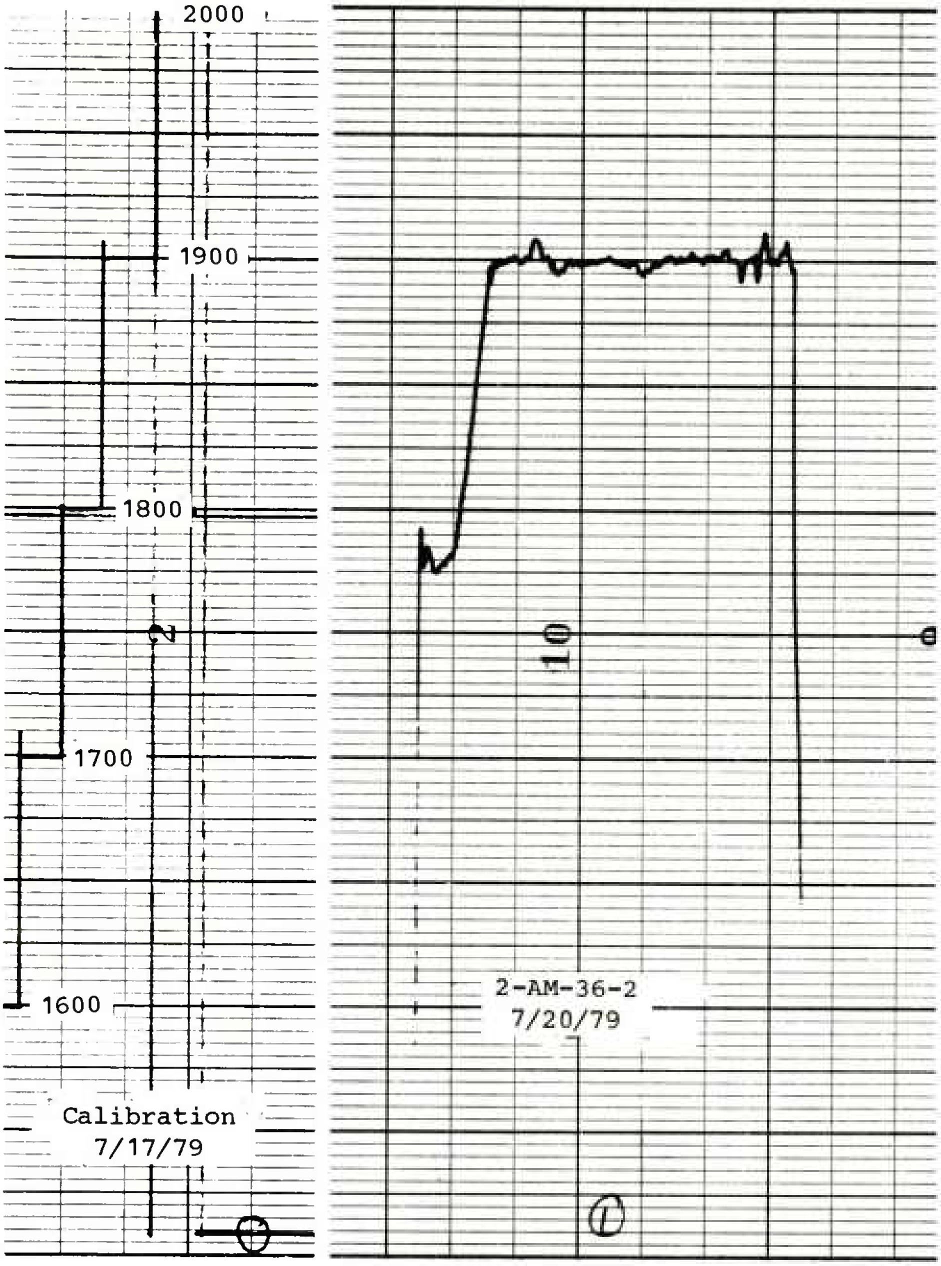


Figure 44. Optical Temperature Feedback Profile During Finish Roll Pass (Blade 2-AM-36)

Table 7

Temperature Control During Finish Roll Forging

	Airfoil Station					
	N	L	J	G	E	C
Temperature (°F)						
Mean	1809	1895	1900	1906	1900	1902
Std. Dev.	35	10	6	17	10	9
Heating Current (KA)						
Mean	21.3	16.3	15.8	14.6	14.3	14.2
Std. Dev.	1.0	1.1	0.6	0.5	0.6	0.4

that exists at the end of the heat-up cycle when airfoil rolling is initiated. Temperature as measured at the remaining five stations was easily controlled at the desired temperature (1900°F) within 20 degrees.

The basic parameters established for finish roll forging of the 2nd stage T55 compressor were:

- 1900°F workpiece temperature
- 33,000 pounds die squeeze at root decreasing to 22,000 pounds at midspan and increasing to 29,000 at blade tip
- 300 pounds front tension
- 1.6 inch per minute airfoil rolling speed.

As shown in Table 8, four blades were given a second finishing pass. This was done to correct an overgage condition found among some of the blades produced prior to use of temperature control. The dimensions were improved and there was no apparent degradation of fatigue properties, as will be discussed below (Section 3.8).

3.6 TASK 6 - EVALUATION OF FORGED BLADES

Blades were evaluated dimensionally in the as roll-forged condition prior to any finishing operations. Metallurgical and mechanical evaluations were made after the hot coining operation and are reported in Section 3.8.

Table 8

Summary of Parameters for 2nd Pass Finish Roll Forging

Blade Code 2-AM-	Micro-Processor Program	Heat-Up: Current Rise Rate KA/Sec	Heat-Up: Current Peak KA	Heat-Up: Die Squeeze Rise Rate KIPS/Sec	Heat-Up: Die Squeeze Peak KIPS	Heat-Up: Duration Sec	Airfoil Roll: Heat Current (KA) / Die Squeeze (KIPS) / Optical Temperature (°F)	Airfoil Station N	L	J	G	E	C	Front Tension KIPS	Duration Sec	Remarks
7	1026	1.92	23.7	1.06	39.3	44	Heat Current (KA)	23	19	14	14	14	15	0.30	118	*
							Die Squeeze (KIPS)	39	39	34	39	39	39			
							Optical Temperature (°F)	NA								
2	1026	2.03	23.7	1.04	40.4	45	Heat Current (KA)	23	16	13	11	11	12	0.30	118	*
							Die Squeeze (KIPS)	40	40	40	40	40	40			
							Optical Temperature (°F)	NA								
32	1026	2.03	23.8	1.23	39.7	45	Heat Current (KA)	23	17	18	16	15	15	0.30	117	
							Die Squeeze (KIPS)	40	40	39	39	39	39			
							Optical Temperature (°F)	1750	1900	1890	1900	1910	1900			
4	1027	0.84	22.9	1.11	33.3	43	Heat Current (KA)	22	10	16	13	17	16	0.30	122	
							Die Squeeze (KIPS)	33	31	23	22	25	29			
							Optical Temperature (°F)	1850	1890	1890	1895	1890	1910			

*Fatigue Test Blade

3.6.1 Dimensional Evaluation

Dimensional evaluation was made by measurement of the maximum airfoil thickness, t_{max}, at the six airfoil stations. This blade feature was used as a measure of quality because it has been found to be the most challenging to control. The airfoil thickness measurements for the batch of 26 blades finished in Phase II after a single finishing roll forge pass are shown in Table 9. The first 8 blades roll forged involved frequent program changes. Three program changes, involving relatively minor adjustments were made while producing the final 18 blades. Also notice that the final 11 blades involved the use of temperature control as opposed to current control on the earlier blades.

The mean thickness for all of the blades falls within the drawing tolerances, except for Station N which lies closest to the root. Figure 45 shows the standard deviation of airfoil thickness for blades produced with the various programs and also for those produced with temperature feedback control. Clearly, the trend is for dimensional deviation to decrease with each subsequent program modification. Temperature control, which in effect represents the combined data from programs 1026 and 1027, indicate an improvement of process control. Additonal work involving a greater number of blades is needed to generate reliable statistical data, but based on the available data it seems highly probable that a second iteration of blade production would produce blades with less dimensional variation.

3.7 TASK 7 - FINAL OPERATIONS

The final operations include the processing steps employed in Phase II that followed the finish roll forge operation. These include the following sequence of operations:

- Rough trim
- Electropolish
- Twist
- Finish surfaces and edges
- Heat treatment
- Finish trim length
- Shot Peen

3.7.1 Rough Trim

The flash at the leading and trailing edges of the finish roll forged blades were trimmed manually by means of a disc grinding machine. This was a simple operation because the flash was thin, the edges of the airfoil was well defined, and the tolerance of +0.005 and -0.025 inch on the chord gave con-

Table 9

Airfoil Thickness of Roll Forged Blades After a Single Finishing Pass
(t_{max} x 10^{-3} inch)

Blade Code	Program	Airfoil Station N	L	J	G	E	C
2	1018	97	77	70	61	48	-
27	1019	93	79	65	59	51	45
26	1020	99	76	56	48	48	44
17	1020	100	79	57	47	39	35
23	1021	101	72	52	44	42	39
33	1022	104	87	67	52	52	53
32	1023	103	84	68	59	55	44
21	1024	96	80	67	57	48	39
7	1025	98	80	69	62	54	46
44		105	93	81	68	56	44
39		100	83	69	56	51	44
28		98	80	68	59	49	41
41		98	80	68	55	49	42
15		96	74	60	49	41	37
4	1026	96	88	79	65	53	42
5*		88	69	60	57	50	42
9*		93	72	61	55	49	41
8*		95	78	67	58	48	40
10*		95	75	61	54	45	40
12*		102	77	63	56	47	41
38*		97	72	62	56	51	42
42*	1027	103	78	62	55	46	40
43*		103	83	66	56	45	38
45*		102	79	64	55	45	40
36*		101	76	60	54	45	38
34*		98	68	58	51	43	34
Mean Thickness		98.5	78.4	64.6	55.7	48.1	41.2
Drawing	Maximum	93.4	83.2	71.4	60.9	51.2	43.7
	Minimum	85.4	75.2	63.4	52.9	43.2	35.7

* Temperature Control

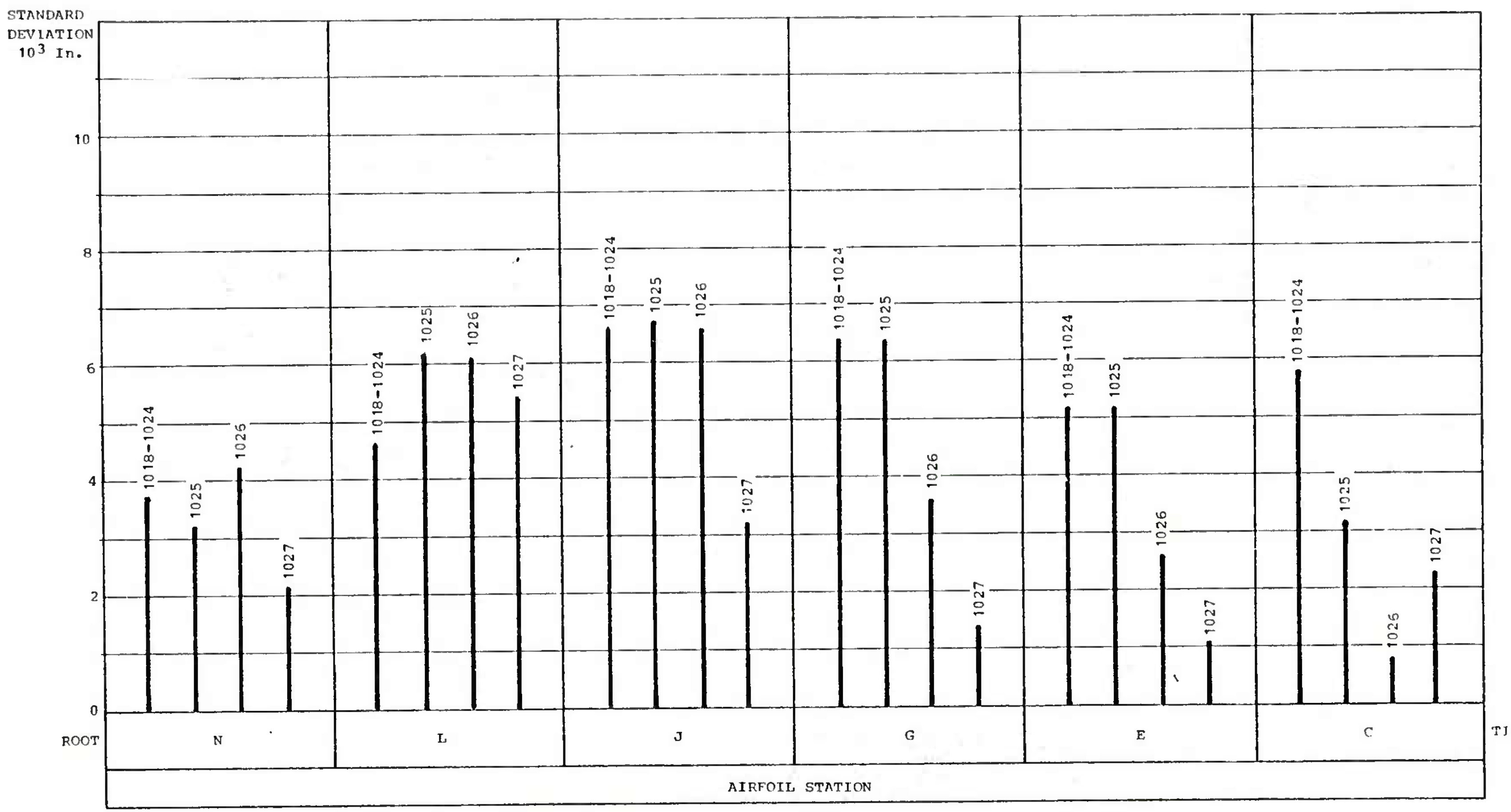


Figure 45. Standard Deviation of Airfoil Thickness of As-Finished Roll Forged Blades as Influenced by Microprocessor Program and Control Mode

siderable latitude. The blade length also was rough trimmed using an abrasive cut-off machine. Special trim dies were not justified for these trimming operations because of the small number of blades processed. Figure 46 shows a typical finish roll forged blade after rough trimming.

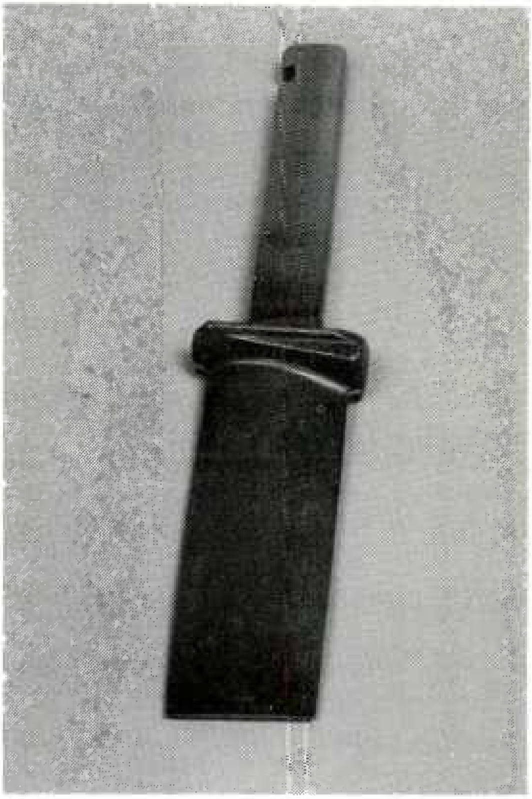


Figure 46.

Finish Roll-Forged AM-350 Blade

3.7.2 Electropolish

The surface contamination problem experienced in Phase I was largely eliminated by use of contoured blade preforms and improved control of the roll forge heat-up cycle. However, with these improvements there remains a carburized layer typically 0.0005-inch in thickness on the surface of finish roll forged AM-350 blades due to diffusion from the graphitic forging lubricant. A commercial electropolishing method was shown effective in removing this thin layer. In production the cost for the cleaning operation would be minimal because multiple blade processing could be employed. Cleaning was performed using the "Summa Cleaning*" process as follows:

> Power-Kleen solution in a stainless steel tank. Flat copper cathodes on each side of blade. Polishing time 6 minutes at 8.0 volts (15 to 20 amps/inch^2) operating at 135 to 145°F. Top water rinse.

The surface of a roll forged AM-350 blade is shown before and after electropolishing in Figure 47.

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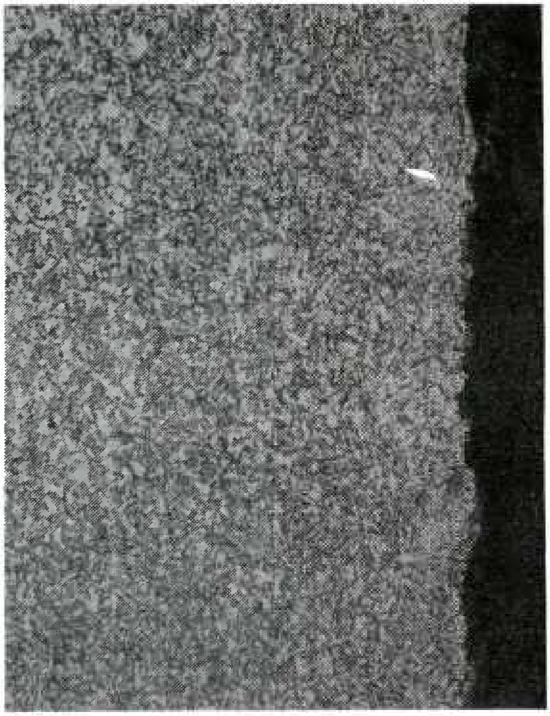
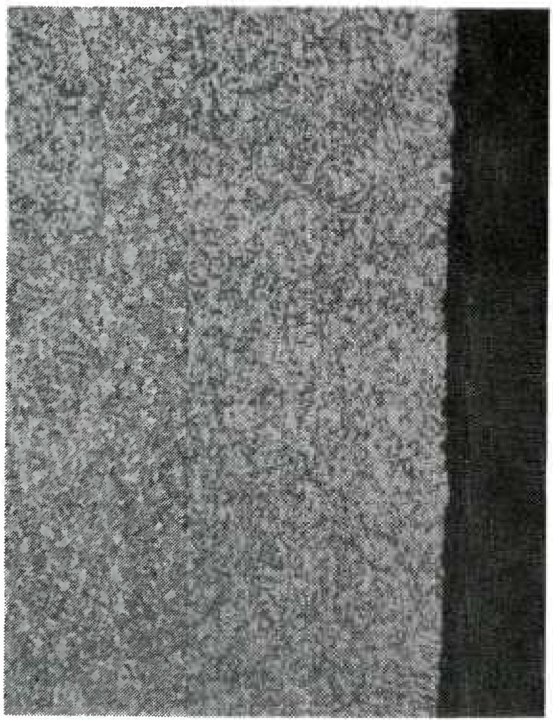
* Molectrics, Inc., Carson, California 90746



A. As Forged



B. After Electropolishing

Figure 47. Surface of Isothermally Roll Forged AM-350 Airfoil Showing the Effect of Post-Forge Cleaning. (Blade: 2-AM-35; Marble's Etchant; Magnification: 500X)

3.7.3 Airfoil Twist

After cleaning, the root stem was removed with an abrasive cut-off machine and twist was imparted to the airfoil on the blade by means of a two-step process. First, the airfoil was twisted at room temperature using a forming technique that involved pressing of the blade into the female twist die using a 1-inch thick pad of medium hard rubber (60 shore) as a punch in a hydraulic press with Magnu Draw 49 lubricant on the blade. A force of 10,000 pounds was found to achieve full contact of the blade airfoil with the die, however, there was considerable springback when the force was removed. This cold forming operation was performed because it was found that the partially twisted blade could more reliably be positioned in the dies for the final hot twisting step.

The hot twisting operation was performed isothermally in resistance heated molybdenum alloy (MT-104) dies. The set-up for hot twisting is shown schematically in Figure 48. The die set is positioned directly upon heater elements which are supported at each end by insulated brackets and in the middle by platens made of a castable ceramic. The dies are heated by thermal conduction from the heater elements which are heated by passage of electric current. Thermocouples located in each of the dies provided for closed-loop temperature control. Figure 49 shows the dies, heater and platens installed in a fourposted hydraulic press. To prevent oxidation of the hot molybdenum dies a protective atmosphere of argon was maintained inside a glovebox enclosure that fits over the press, as shown in Figure 50. This enclosure has a vacuum lock at one end through which the blades were transferred for processing. The twisting of AM-350 blades was evaluated at die temperatures ranging from 1700 to 1940°F at die squeeze forces from 6,000 to 15,000 pounds for time intervals from 2 to 20 minutes. The pressing schedule adopted was:

- Die temperature 1900 to 1920°F.
- Preheat blade between dies for 1 minute at low force.
- Apply 12,000 pounds of squeeze and hold for 2 minutes.
- A thin coating of magnesium oxide (Milk of Magnesia diluted 1 to 1 with water) applied to the blade was found to be an effective, noncontaminating release agent.

Blades twisted with this schedule conformed to the dies, had no apparent springback, were easily ejected by tapping the end of the root, and were found to be in the solution heat treat condition. The blade roots were squeezed to a thickness of typically 0.360-inch and a very thin flash formed at the trailing edge of the airfoil for a distance of about 0.6 inch from the root.

3.7.4 Surface Finishing

Surface finishing of the airfoil was accomplished by means of manual trimming of the flash, Sweco vibratory finishing of the airfoil and edges supplemented with manual blending of the airfoil into the fillet radius and root platform with a rotary buffing tool.

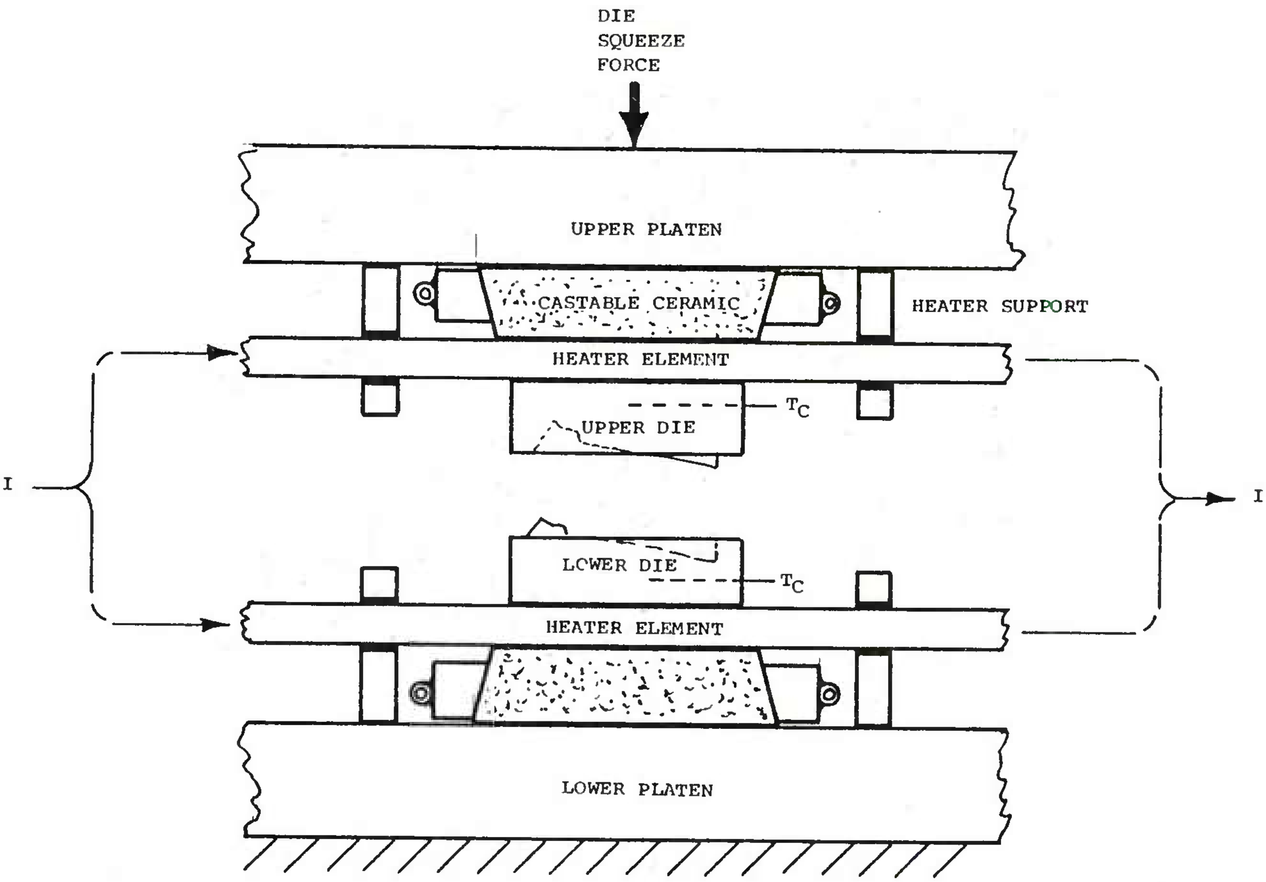


Figure 48. Schematic Diagram of Hot Coining Press Used to Impart Twist to the Blade Airfoils

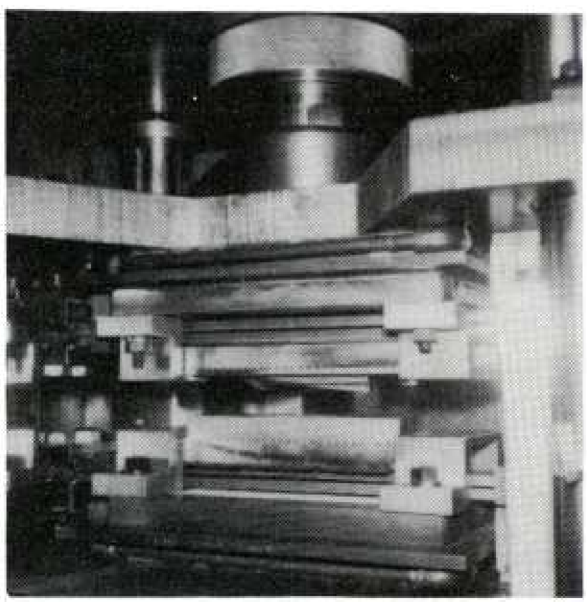


Figure 49. Interior of Hot Coining Press Showing Twist Dies

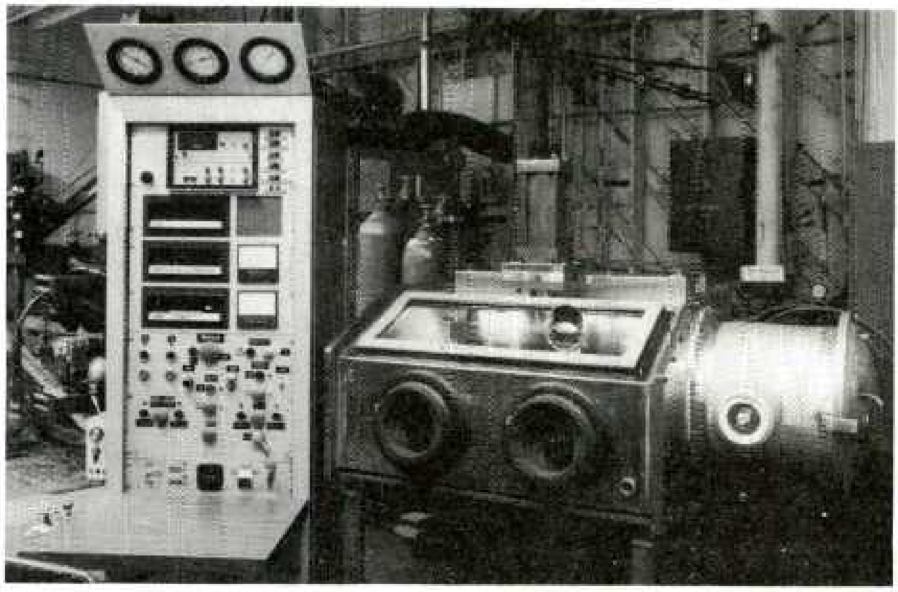


Figure 50. Hot Coining Press and Control Panel (#80-1286)

3.7.5 Heat Treatment

The finished blades were heat treated at Solar in accordance with Avco Specification F7703E, Amendment 4. The heat treat schedule was:

1. Equalize 1425 ± 25°F 3 hours in argon. Air cool to RT.

2. Overtemper 1075 ± 25°F 3 hours in air circ furnace. Air cool to RT.

3. Harden 1710 ± 10°F 15 minutes in range 1700-1720 in argon. Fan air cool to RT.

4. Subzero cool -100°F 3 hours or more in dry ice/acetone bath. Warm to RT

5. Temper 1000 ± 10°F 3 hours in air circ furnace. Air cool to RT.

The thin oxide that formed during heat treatment was removed with a light sandblast using 150 mesh garnet sand at 40 psi air pressure.

3.7.6 Finish Trim Length

The final processing step at Solar was trimming the blade tip to length. This was done by clamping the dovetail of the root in a fixture and soaking the blade tip while on a surface plate. The tip then was ground to the scribe line with a disc grinder using care to avoid overheating. The first batch

consisting of 19 finished blades is shown in Figures 51 and 52. A close-up photograph of an individual blade is shown in Figure 53.

3.7.7 Shot Peening

Following visual and magnetic particle inspection by Lycoming, the blades were glass bead peened by a Lycoming certified vendor prior to the initiation of fatigue testing.

3.8 TASK 8 - EVALUATION OF FINISHED BLADES

The evalution of finished blades included visual and magnetic particle inspection, dimensional inspection and analysis, chemical analysis, fatigue tests and metallographic analysis. All of this work was performed by the Lycoming Division of Avco Corporation, except the dimensional inspection and anlayses which were done at Solar.

3.8.1 Visual and Magnetic Particle Inspection

Lycoming reported:

> "Upon receipt at Lycoming the blades were visually and magnetic particle inspected. There was no evidence of airfoil anomalies, however, nearly all of the blades exhibited laps or voids in the as-forged root some of which would have been removed by subsequent root form machining operations. The blades were glass bead peened per engineering drawing requirement prior to the initiation of fatigue testing."

A typical example of the forging defect found in the as-forged root is shown in Figure 54. Superimposed is the outline of the finished machined root which shows that in the typical case the forging defect would be removed by the normal root broaching operation. Forging trials have shown this defect to be caused by the formation of a secondary bulge that tends to form during the final seconds of the root injection operation.

The forging laps, when found, are at the dovetail end of the root and never at the platform end. Formation of the secondary bulge is influenced by several factors, including heating time prior to upsetting, rate of upsetting, and support of the metal as it enters the dies. The fact that it does not always occur suggests that the undesirable secondary bulge can be eliminated by systematic control of these factors.

3.8.2 Dimensional Inspection and Analysis

As expected, the most difficult blade feature to control has been thickness of the airfoil (t_{max}). Other blade features which include root fillet radius, airfoil section envelope, chord, twist and straightness presented relatively

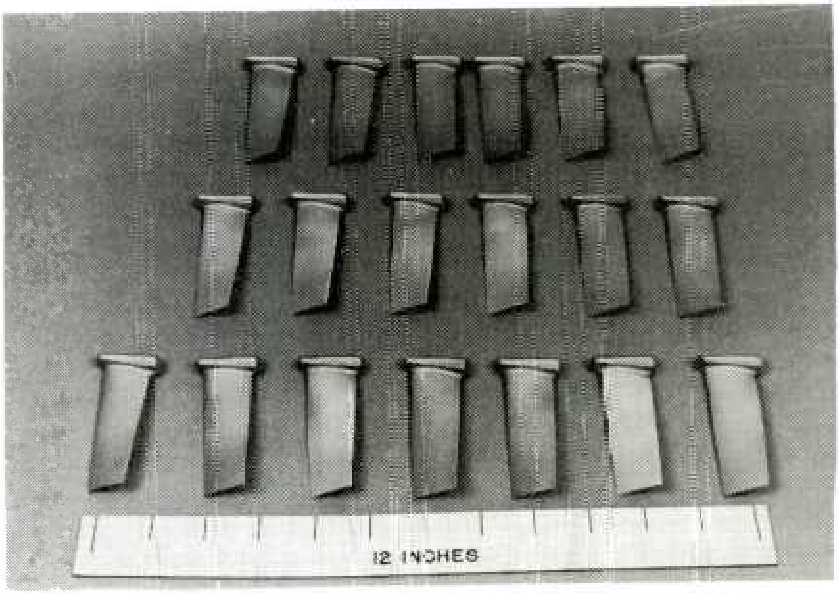


Figure 51. Finished Blades Produced in Phase II, Suction Side (#79-3871)

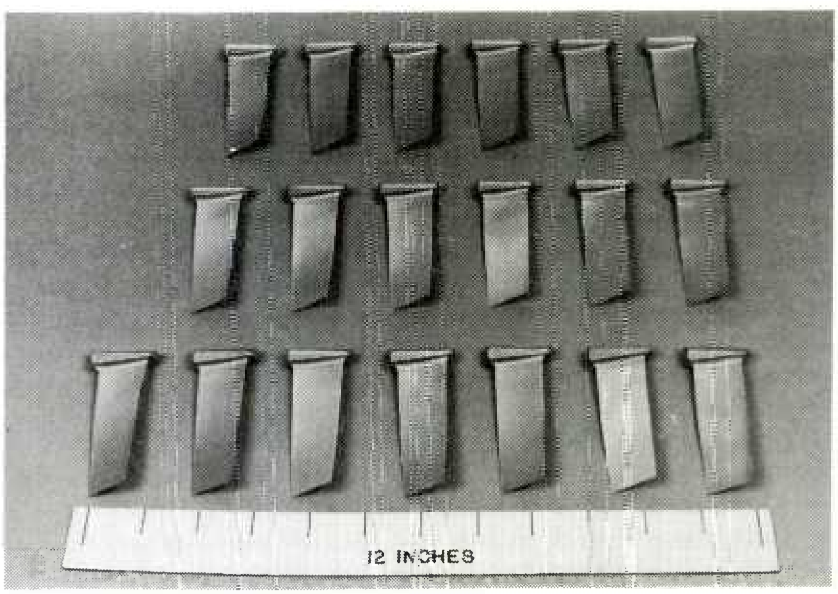


Figure 52. Finished Blades Produced in Phase II, Pressure Side (#79-3871)

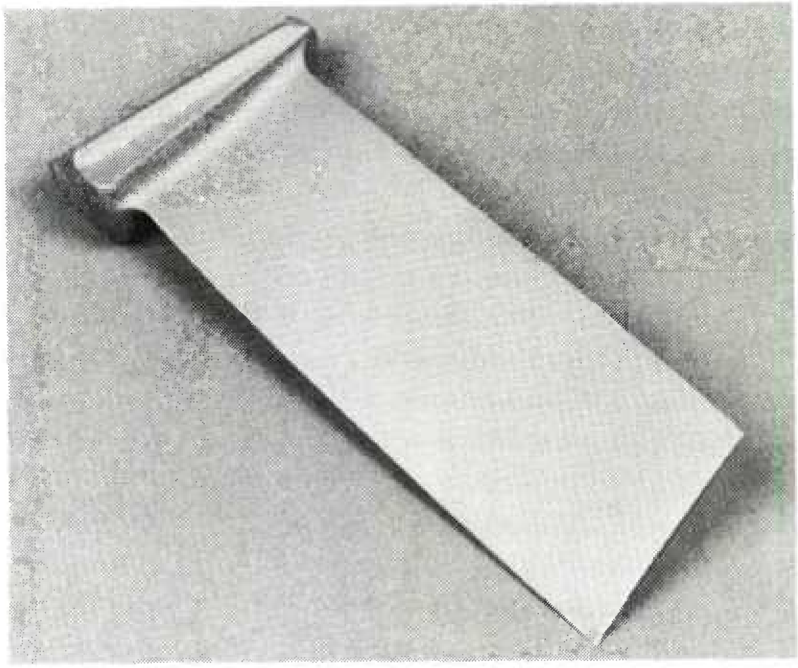


Figure 53. Close-Up View of a Finished Blade (#79-3873)

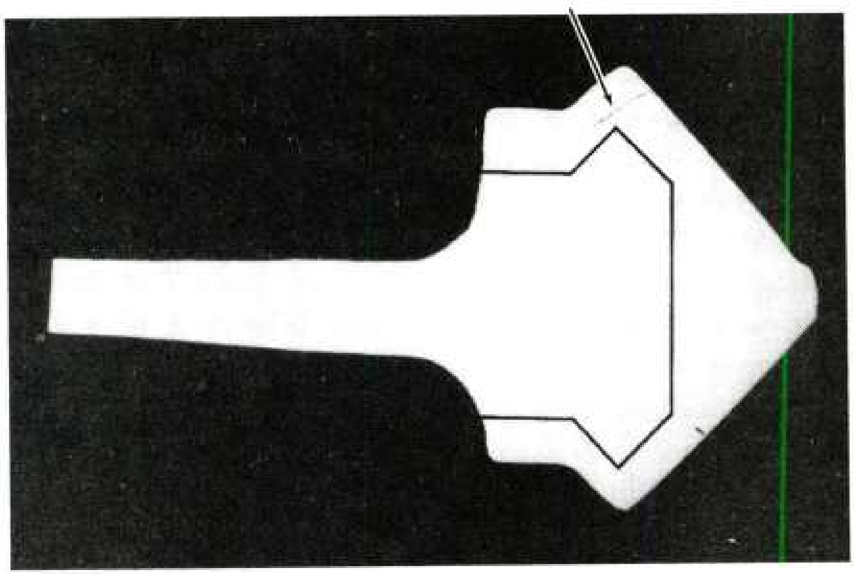


Figure 54. Macrosection of Finish Forged Blade Root Showing Forging Defects and Outline of Finished Machine Contour. Magnification: 5X

minor control problems which were largely solved during the limited forging experience of Phase II. Section envelope is initially determined by the die contours and the maintenance of precision location of the dies in the forging machine. Both are straight-forward tooling requirements which were adequately controlled in Phase II. The final consideration in envelope control is die wear. Experience in forging some 50 blades in AM-350 suggests that envelope control is not a problem after a near optimum forging schedule, such as program 1027 for finish roll forging, is established. Die wear that does occur under such conditions, is largely confined to the flash lands. Lateral flow of flash across the flash lands tends to displace the tip of the lands in the direction of flow. From this work it appears that airfoil envelope, including that adjacent to the leading and trailing edges, can be economically controlled but that control of edge radii will require trimming and finishing subsequent to roll forging, as is required in conventional blade manufacturing.

Chord, width of the airfoil, has a 0.030-inch tolerance band on the program blade and control of this feature presented no problems in Phase II. Twist and straightness of the airfoil appears to be completely controlled by the hot coining operation used in Phase II. After coining, the blades nested perfectly in the coining dies with no apparent springback.

A survey of airfoil thickness control was made on the finished blades just prior to shipment to Lycoming. These data are presented in Figure 55 and Table 10. These data represent an improvement over the blades of Phase I,

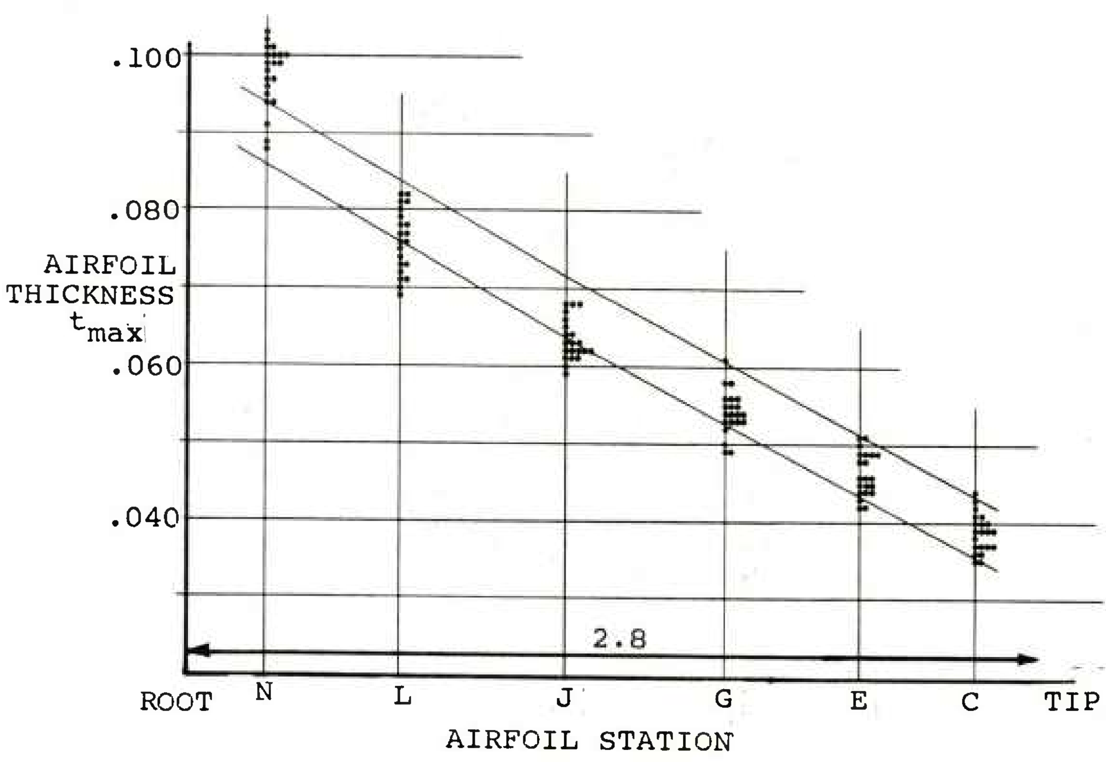


Figure 55. Maximum Airfoil Thickness of T55 Blade
(First Roll Forged Batch (21)

Table 10

Airfoil Thickness of Blades Evaluated by Avco Lycoming
[t_{max} (10^{-3} inch)]

Blade Code	Airfoil Station					
	N	L	J	G	E	C
2	85	69	57	52	47	40
5	90	70	60	55	50	42
7	89	69	59	52	45	37
8	91	77	65	57	47	39
10	95	73	60	53	44	36
12	104	77	62	55	46	39
21	98	80	67	56	47	39
26	98	78	58	49	48	43
28	99	81	67	58	48	39
33	102	85	66	52	52	52
34	91	66	55	49	40	32
39	100	83	66	53	48	42
42	103	77	61	53	44	36
43	103	81	64	54	43	36
44	97	74	59	54	49	43
Mean	96.3	76.0	61.7	53.5	46.5	39.7
Standard Dev.	5.90	5.67	3.88	2.56	3.00	4.58
Excluding Blades 33 & 34						
Mean	96.3	76.1	61.9	53.9	46.6	39.3
Standard Dev.	5.96	4.73	3.50	2.36	2.10	2.59

however additional improvement is needed. These represent the first batch of 21 blades produced by the process. In Phase II it was planned to include a second processing iteration to decrease the dimensional variation and to increase the number of blades within the tolerance band. Unfortunately, this was not possible in order to meet the delivery schedule.

3.8.3 Chemical Analysis

The chemical composition, retained austenite and hardness of a sample blade were measured and evaluated by Lycoming per engineering drawing and LES M3709 material requirements. As shown in Table 11, these properties were in conformance.

3.8.4 Fatigue Tests

Lycoming reported:

> "All fifteen blades were subjected to air jet excitation "beehive" fatigue testing (room temperature) in the first bending mode to compare their high cycle fatigue capability to that of conventionally fabricated production blades of the same configuration. The blades were excited to preselected amplitudes by high pressure air directed at the airfoil tips in the vertical plane and tested to fracture. Strain gaged blades were used to determine the stress at the origin of fatigue as a function of blade tip displacement.

Table 11

Chemical Analysis and Hardness of a Solar Forged Blade

Element	LES M3709 Requirements	Test Results
C	0.08-0.12	0.09
Mn	0.50-1.25	0.69
Cr	16.00-17.00	16.69
Ni	4.00-5.00	4.23
Mo	2.50-3.25	2.67
N	0.07-0.13	0.08
Fe	Balance	Balance
Retained Austenite	15.0% max.	12.3%
Hardness	HRC 35-44	HRC 38

The plane of fracture of the test group varied from 1/16 to 1/14 inches above the root section [Figure 56]. This was considered to be a large test scatter since conventionally manufactured blades tested in a similar manner fracture within 0.5 inch of the root. The scatter may be a result of the dimensional anomalies in gage thickness reported by Solar. Four blades were retired after 3 million cycles and were later step loaded to induce failure. A statistical analysis of data [Table 12] was performed and the resultant endurance limit curves are shown plotted in [Figure 57] with the test points superimposed. The average fatigue limit was 110,460 psi compared to 112,000 psi for current production blades with the stress for one failure in 100 samples of 95,944 psi compared to the minimum aceptable (1 in 199) endurance limit for new blades of 95,000 psi. It should be noted that because of the significant scatter in fracture locations the most conservative of three calibration factors was used to establish the stress vs blade tip displacement for this analysis."

To avoid the high set-up costs for broaching, it was decided to test the above blades with roots in the as-forged condition. The as-forged dimensions of the root surfaces which were clamped in a special holding fixture for fatigue testing were 0.355 ± 0.005 inch.

The two blades which fell significantly below the upper curve (mean) in Lycoming's figure (Fig. 57) were blade Nos. 34 (lap defect) and No. 44. Examination of the forging records for these blades may explain the lower fatigue results. The root of blade No. 34 had experienced overheating during the finish roll forge pass (see Table 5). Also blade No. 44 which had been used to establish the hot coining twist operation had been exposed to the 1800 to 1920°F temperature range for about three times the duration finally established for a good part of this excessive time a graphitic die lubricant had been used with blade No. 44. The graphitic lubricant was later replaced with a magnesium oxide lubricant because it proved adequate as a die release and had less propensity for blade contamination.

Analysis of the location of fatigue fractures shows a near perfect correlation with deviation from nominal of airfoil thickness. With but one exception (blade #39), all of the blades fractured either at a point of maximum negative deviation from nominal or at a point of abrupt change from a positive deviation. Both situations would create a stress riser. Examples of the two typical situations are shown in Figure 58. The conclusion from this analysis is that the origins of the fatigue fractures were primarily determined by dimensional rather than by metallurgical and surface factors.

3.8.5 Metallographic Examination

Lycoming reported:

"Each airfoil fracture surface [of the fatigue tested blades] was examined utilizing a binocular microscope to determine if any anomalous condition influenced the fracture location or test result. One airfoil was found to have a lap at the origin which likely caused that crack

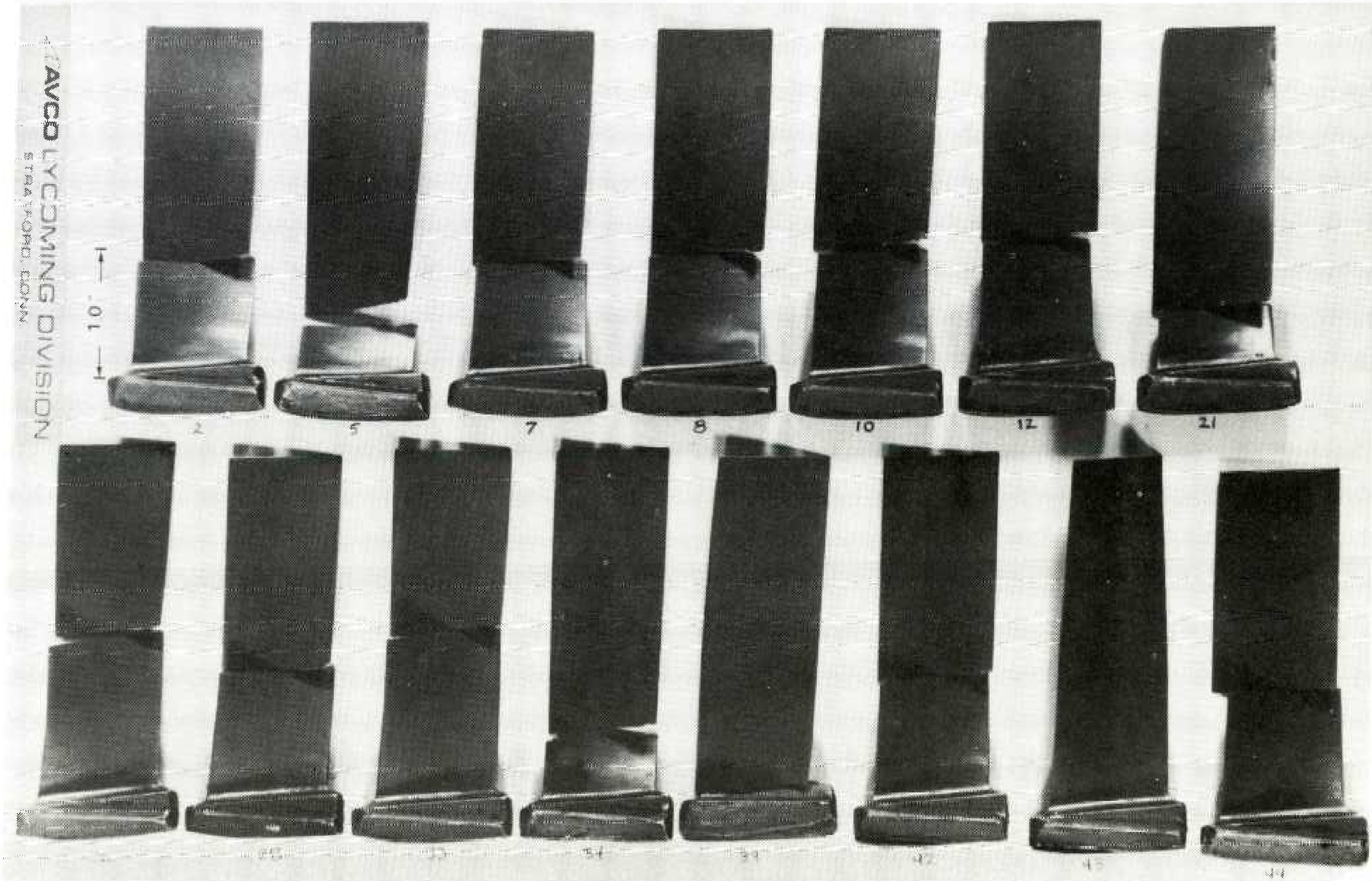


Figure 56. View of the Concave Side of the Solar Blades Showing the Locations of Fatigue Fracture

Table 12

Summary of Results
Beehive Fatigue Test and Statistical Analysis

Number of Samples		15
Natural Frequency	Average (Hz)	413.9
	Standard (Hz) Deviation (%)	46.23 11.2
Average Fatigue Limit (±psi) 50% Failures		110,460
Standard Deviation (±psi)		6231.7
Average Fatigue Limit (±psi) 1 Failure in 100 Samples (New Blades)		95,944 (95,000)
Mean-3 Standard Deviation (±psi)		91,769
Low Limit Fatigue Limit (±psi) 1 Failure in 10,000 Samples (95% Confidence Band)		74,960
Calibration (±psi/MIL P-P)		222.0

to initiate prematurely on the concave side of the airfoil. Twelve of the fourteen failed blades exhibited fatigue crack initiation points on the convex side near mid chord; this is more characteristic of new compressor blades. One representative fracture [Figure 59] was further examined with a scanning electron microscope (SEM). The fracture morphology [Figure 60] was typical of that seen in conventionally fabricated AM-350 blades which have been similarly tested. One half of this fracture was sectioned at the origin for metallographic study. There was no evidence of microscopic material anomalies associated with the fatigue origin [Figure 61]."

The representative microstructure of a finish blade is shown in Lycoming's figure (Fig. 62). The microstructure of the finished blade was judged by Lycoming to be in conformance with LES M3709.

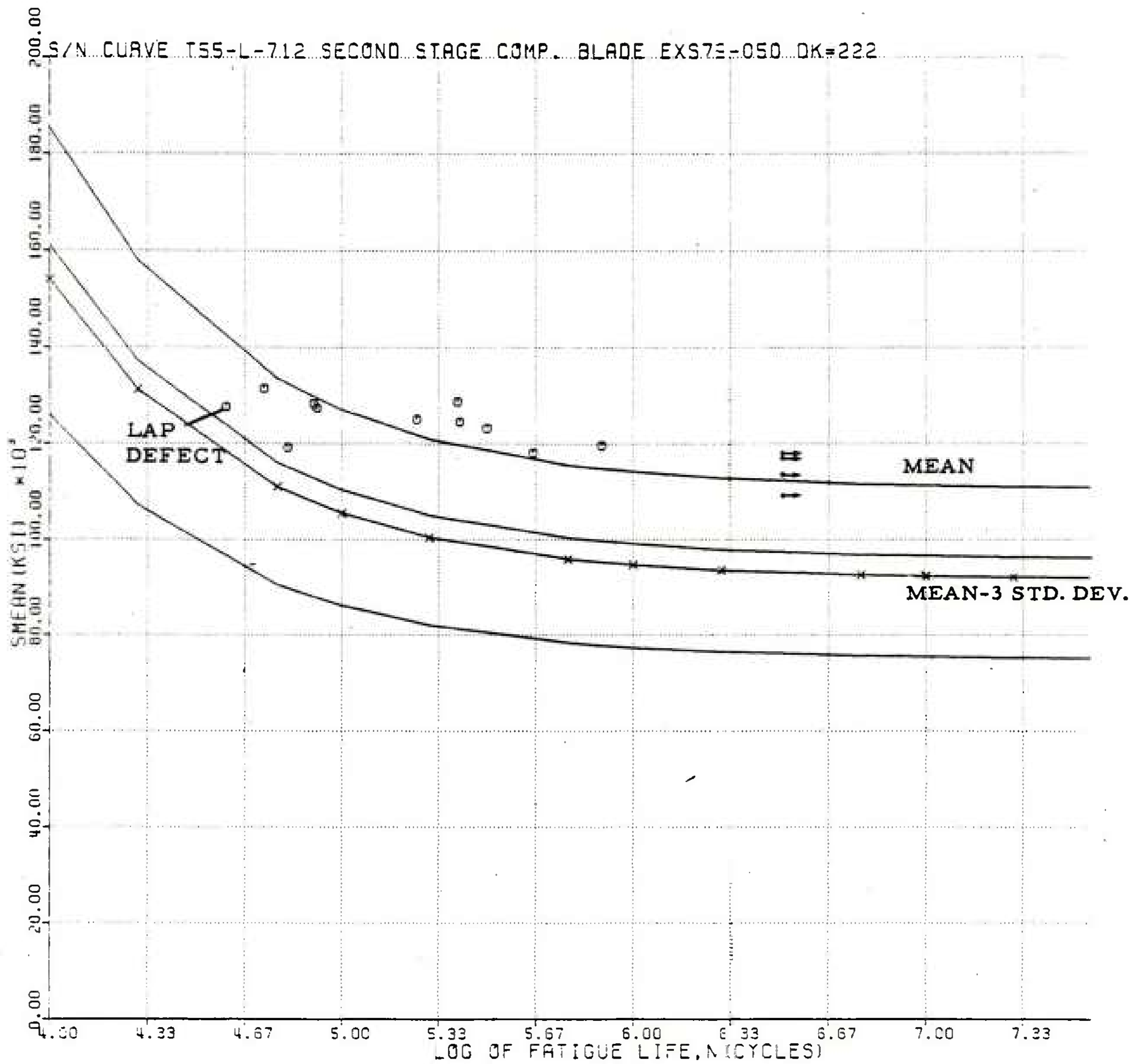


Figure 57. Beehive Fatigue Test Results (alternating vs. cycles to failure)

3.9 TASK 9 - PROCESS SPECIFICATIONS

3.9.1 Procurement and Certification of AM-350 Feedstock

This specification is based on Avco Specification No. M3709C which covers their general requirements for AM-350 steel, modified for the specific requirements of the isothermal roll forge process.

Melting Process

The steel shall be produced by multiple melting using consumable electrode practice in the final remelt cycle.

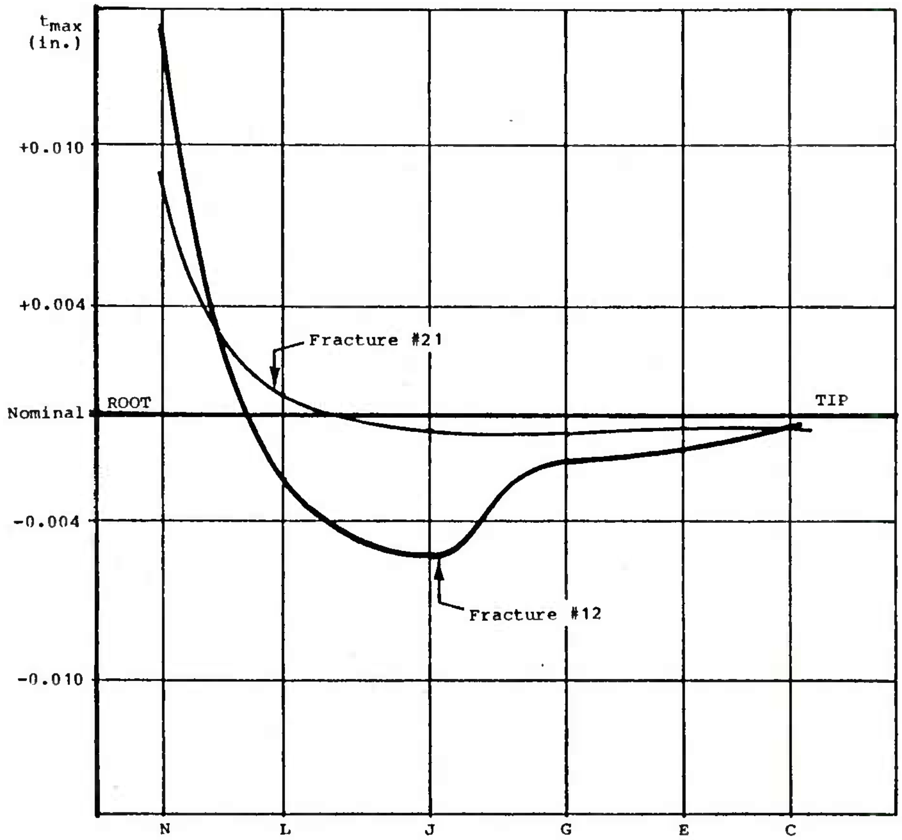


Figure 58. Two Typical Blade Airfoil Thickness Contours Showing Location of Fatigue Fractures

Condition

The bars of feedstock shall be delivered in the solution treated and pickled condition (Condition H) with a hardness of HRC 18 to 24.

Size

The requirement of a given blade will determine the thickness and width of the feedstock. For the T55 second stage blade a size of 0.250 x 0.500 inch in random lengths of 12 feet was specified with a tolerance of ±0.004 inch on the thickness and width dimensions.

Chemical Composition

Element	Minimum	Maximum
Carbon	0.08	0.12
Manganese	0.50	1.25
Silicon	--	0.50
Phosphorus	--	0.040
Sulfur	--	0.030

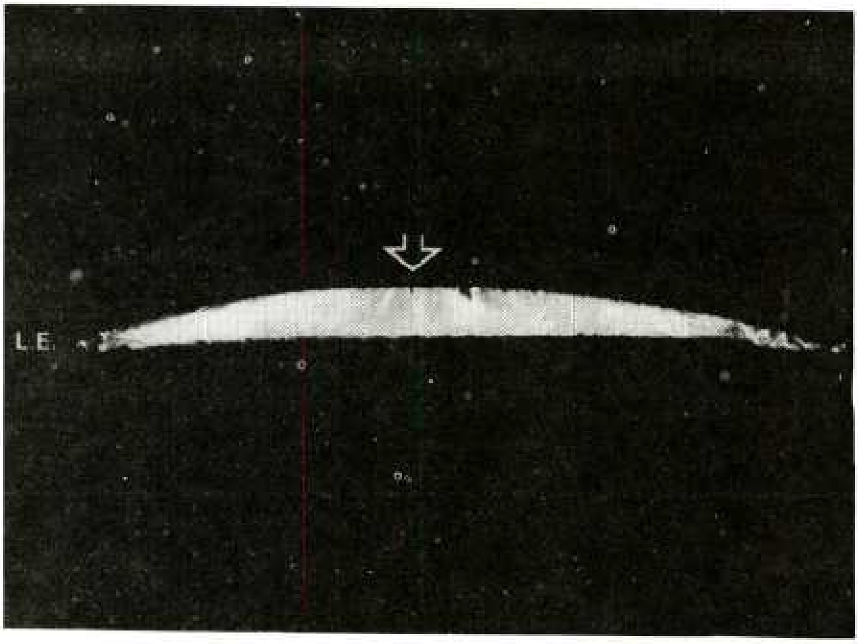


Figure 59. Overall View of a Typical Fatigue Fracture (arrow at origin). Magnification: 4.5X

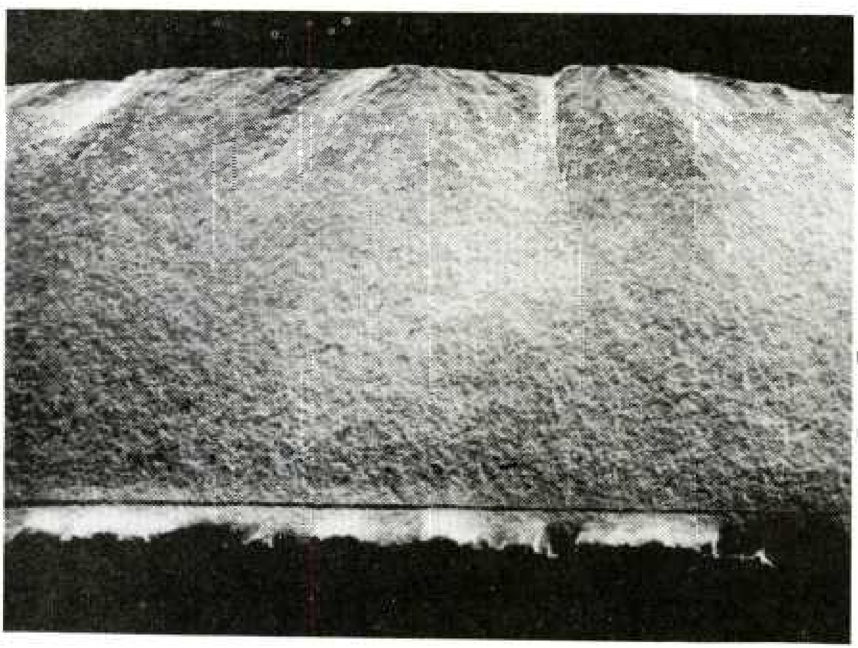


Figure 60. SEM Close-Up of the Fatigue Origin Shown in Figure 59. Magnification: 40X.

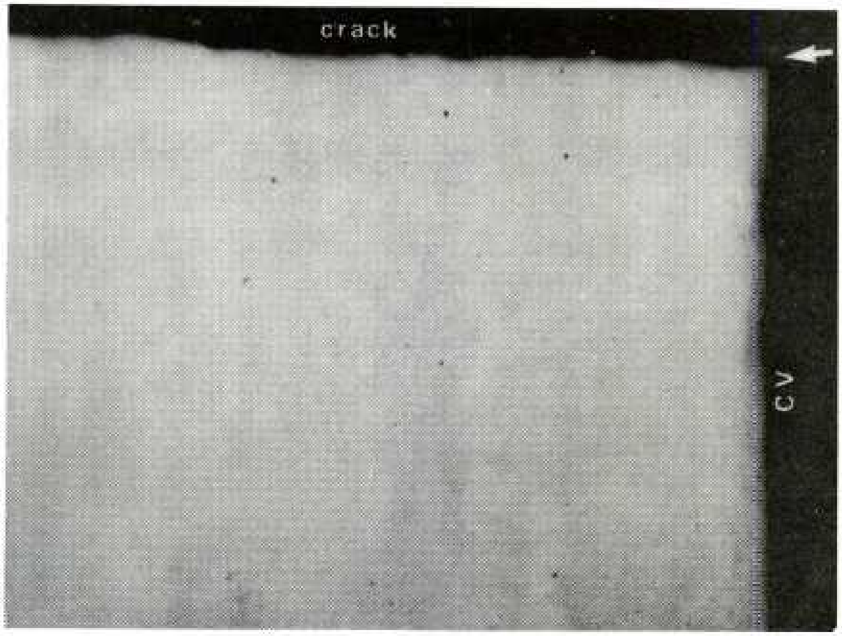


Figure 61. Polished Section Through the Fatigue Origin (arrow) Shown in Figures 59 and 60. Magnification: 200X

Figure 62. Photomicrograph Showing the Microstructure of the Subject Blades. Magnification: 500X; Etchant: Dilute Marbles

Element	Minimum	Maximum
Chromium	16.00	17.00
Nickel	4.00	5.00
Molybdenum	2.50	3.25
Nitrogen	0.07	0.13

Composition variations shall meet the requirements of Specification AMS 2248.

Properties in the Fully Heat Treated Condition

Tensile - When a tensile test specimen is tested in accordance with the requirements of Standard ASTM E8, the tensile properties shall be as follows:

Tensile Strength, min	165,000 psi
Yield Strength at 0.2% offset, min	140,000 psi
Elongation, % in 4D	10 min
Reduction of Area, %	20 min

Hardness - The hardness of hardened and tempered steel shall be HRC 35 to 44 or equivalent.

Microstructure - Microstructure specimens taken in a longitudinal direction from random areas of the feedstock and polished and etched shall exhibit the following properties:

a. Structure - The structure shall be tempered martensite and small grained delta ferrite.

b. Carbide Precipitate - A small amount of discontinuous carbide precipitate shall be permitted within the martensite grains or at the junction of martensite and delta ferrite.

c. Retained Austenite - A maximum of 15 percent of retained austenite shall be permitted. The referee method of retained austenite determination shall be X-ray diffraction.

The etchant shall be marbles reagent mixed with equal parts of water and used at room temperature. The reagent shall be formulated as follows:

Copper Sulphate ($CuSO_4$) - 20 grams

Hydrochloric Acid (HCl) - 100 millimeters

Water - 100 millimeters

Grain Size - The grain size shall be ASTM number 5 or finer when measured in accordance with Standard ASTM E112.

Macrostructure - The bars shall not exhibit any evidence of inclusions, segregation, stringers, laps, seams, etc., when visually examined after macroetching.

Macroetching - The specimen shall be immersed for 20 minutes in a solution of equal parts by volume of concentrated hydrochloric acid (HCl, 37%) and water heated to a temperature of 160 ± 10°F.

Quality - The material shall be uniform in quality and condition, clean, sound and free of foreign materials or internal and external imperfections detrimental to fabrication or performance of blades.

3.9.2 Preparation of Preforms

Requirement

The blade feedstock shall be contoured on one pair of opposing faces in such a manner that line contact is created when the forging dies close up on the feedstock. By avoiding point contacts the life of the forging dies extended and localized overheating of the feedstock is is avoided at the initiation of the heat-up cycle.

Configuration

The preform configuration required for the 2nd stage blade of the T55 engine was shown in Figures 13 and 16. Basically it consists of a convex face with a 1.00 inch radius and a concave face with a 1.80 inch radius.

Procedure

The required configuration can be produced readily in AM-350 alloy by cold rolling the material in the solution treated condition (Condition H). For the T55 blade preform the required contours were produced by a single pass through a Turk's Head roll cluster which produced a thickness reduction of about 7 percent. The feedstock was drawn through non-powered rolls at a speed of 0.5 feet per second using Magnu-Draw 40 lubricant on the rolls.

To avoid buckling during the root injection of the roll forge cycle, it is necessary to increase the compressive strength of the preforms by heat treatment. A simple equalize and overtemper heat treatment is adequate.

Equalize:
1. Heat to 1425 ± 50°F
2. Hold at temperature for 3 hours minimum
3. Air cool to room temperature

Overtemper: 1. Heat to 1075 ± 25°F
2. Hold at heat for 3 hours minimum
3. Air cool to room temperature

The cold rolled and heat treated feedstock is cut to length using an abrasive cut-off machine. Automatic vibratory tumbling with abrasive media is used to radius the sharp edges are to 0.010 to 0.020 inch. This operation also removes surface scale produced during the heat treatment and conditions the surface for application the forging lubricant. In Phase II a preform with a length of 8.50 ± 0.03 inch was used.

Just prior to use, a coating of lubricant is applied to the blade preform. The coating must be both an electrical conductor and a high temperature lubricant. It must be thick enough to function as a lubricant and release agent, but not so thick as to significantly interfere with thermal conduction between the workpiece and dies. Sprayon Dry Graphite Lubricant No. 24 (when properly applied) meets these requirements. From a distance of 8 to 10 inches spray the coating with two passes transversing at a rate of approximately 4 inch per second. This builds a coating of approximately 0.0002-inch in thickness.

3.9.3 Rough Roll Forging

Machine Set-Up

Program the control system of the isothermal roll forging machine to regulate the heating current, die squeeze force and the time sequencing of process events, which includes initiation of heating cycle, actuation of hydraulic rams and electric motors. A program such as No. 1017 shown in Table 3 is satisfactory.

The open loop parameters of root injection force, tip feed force, front tension force and die rotation motor speed are preset to the desired levels.

The roll forge dies are installed and aligned laterally and adjusted for relative angular position and die gap (blade thickness).

Blade Forging

The root pockets of the dies are aligned in the root injection position and the mechanial stops are set against the top faces of the die support blocks (see Fig. 20). The blade preform is inserted into the lower nozzle. The upper nozzle is lowered against stops and the upper ram is brought into contact with the upper end of the preform. The atmosphere covers are positioned and the argon purge initiated. The microprocessor is keyed and the forging cycle proceeds automatically except for operator adjustment of heating current to maintain the desired forging temperature as indicated by the optical pyrometer. At the conclusion of the cycle the heating current is off, the dies are open, the tip feed ram is in the retract position, the upper nozzle and ram have ascended, and the rough forged blade is suspended from the upper nozzle. Removal of the blade completes the cycle.

3.9.4 Intermediate Operations

The intermediate operations include flash trim, surface cleaning and relubrication in preparation for the finish roll forge pass.

Trim the flash by means of a conventional blanking operation. For this operation position the blade in the blanking fixture by means of two points on the root platform and one point at the trailing edge of the root. Deburr the sheared edges and clean the surfaces by tumbling in a Sweco-type vibratory finisher. Relubricate as described in Section 3.9.2.

3.9.5 Finish Roll Forging

Machine Set-Up

Program the machine as described in Section 3.9.3 on rough roll forging; however, in this case use a program such as No. 1027 shown in Table 6.

Adjust the open loop parameters as described earlier to the levels required for finish roll forging.

Adjust the die gap by placing precision ground spacers behind the dies to produce the required blade thickness.

Remove the tip feed ram from the machine and lower the lower nozzle 2 inches by means of a spacer ring. This change will accommodate the length of the rough roll forged blade.

Blade Forging

The principal differences in machine functions between finish and rough roll forging are the substitution of root squeeze in place of root injection and elimination of tip feed force during the finish roll forging. The root pockets of the dies are aligned as before so as to close up on and squeeze the existing blade root. The mechanical stops are set to eliminate backlash in the drive system and to insure root pocket alignment. The root end of the rough forging is inserted into the upper nozzle and latched into place. The upper nozzle is then lowered against stops that align the existing root with the root pockets of the dies, while the tip end of the forging enters the lower nozzle. The lower nozzle serves only to guide the blade during the finish roll of the airfoil. The operator requirements for the rest of the cycle are identical to those described for rough roll forging.

3.9.6 Finishing Operations

Flash and Tip Trim

Trim the flash from the edges of the airfoil and trim the excess length from the blade tip using a conventional blanking die. As before, positioning is

on the root platform and trialing edge end of the root. Trim the edges to chord tolerance and leave about 0.1 inch on the tip.

Surface Cleaning

Vapor degrease, and remove forging the lubricant and oxide film by tumbling in a vibratory finisher. Electropolish in Power-Kleen* solution to remove about 0.0005 inch of material on the surface of the airfoil and about 0.005 inch from each edge. This takes about 6 minutes at 8 volts.

Stem Trim

Clamp the dovetail of the roll forged blade root in a fixture and trim away the non-forged feedstock by abrasive cut-off using coolant to avoid overheating of the root.

Airfoil Twisting

Pretwist the finished roll forged blades at room temperature by pressing the suction side of the blade against a hardened steel twist die using a high pressure metal drawing lubricant such as Magnu-draw 40 and a 1-inch thick 'unch consisting of medium hard rubber (60 shore). A momentary force of about 5 tons is adequate to pretwist the T55 second stage blade. The blades are pretwisted to insure proper seating during the subsequent hot coining operation.

Degrease the pretwisted blades and apply a release agent by spraying a thin coating of Milk of Magnesia diluted 1 to 1 with water. Preheat the molybdenum alloy twist dies to 1900 ± 20°F in the coining press. Position the blade into the lower die (suction side down), close the dies under low force (<200 lb), wait 1 minute for the blade to reach temperature, squeeze at high force (12,000 lb) for 2 minutes, open the dies and remove the finish blade.

Edge Finishing

Remove the hot twist release agent by soaking the twisted blades in hot water. Hand finish the edges of the airfoil (a small flash may have formed during the hot twisting operation).

Heat Treatment

The AM-350 blades after hot twisting, are in the solution heat treat condition from which condition the final heat treatment can be completed by equalizing, hardening and tempering.

Equalizing:
1. Heat to 1425 ± 25°F
2. Hold at heat for 3 hours
3. Air cool to below 150°F then water cool to below 70°F

4. Heat to 1075 $\pm$ 25°F
5. Hold at heat for 3 hours
6. Cool in air

Harden:

1. Heat to 1710 $\pm$ 25°F in protective atmosphere
2. Hold at heat for 5 to 15 minutes
3. Rapid cool with circulating air to below red heat
4. Air cool to room temperature
5. Cool to at least -100°F for 3 hours
6. Warm in air to room temperture

Temper:

1. Heat to 1000$\pm$ 10°F in air circulating furnace
2. Hold at heat for a minimum of 3 hours
3. Air cool to room temperature.

Final Machining

The root is finished and blade length trimmed using conventional broaching and shearing methods. Stress relieve after final machining by heating to 960 $\pm$ 15°F for 2 hours

Final Surface Finishing

Glass bead peening shall be performed in accordance with Specification AMS 2430.

3.10 Cost Analysis

The technology of isothermal roll forging of compressor blades has been advanced considerably in Phase II of this program. Cost projections were made before the program started, and again at the end of Phase I. In each case the cost estimates were found to have been conservative based on the experience at each step. This is a most important point because in the absence of hard data on even small quantity production (e.g., several hundred blades) cost estimates are most difficult to project.

Before the start of Phase I, cost estimates wre made for titanium blades and showed a clear cut advantage over the conventional method of manufacture. Very early in Phase I, a change to AM-350 alloy made cost savings less certain. However, by the end of Phase I, experience with AM-350 showed that it could be shaped at 1900-1950°F, similarly to titanium alloy at 1700-1750°F. As a result, cost savings were predicted based on the marked reduction in the number of operations (see Table 9 of AVRADCOM Report No. 77-11). In the present phase, another major technical step has been introduced with use of a microprocessor. This has increased reproducibility, decreased scrap losses, and decreased the overall operational time. As a result, confidence in a significant cost reduction has increased.

Although projection from the current work to volume production remains difficult, an updated cost analysis has been prepared and is presented below. The analysis does not include amortization of investment and other cost contributors because of the uncertainty in these factors in the present investment climate. The analysis covers the times required for each operation in the manufacturing process. It is based on an assumed quantity of 10,000 blades.

3.10.1 Operational Costs

	Minutes Per Blade
1. Preform preparation from bar	
Turk's Head roll Cut to length Cut notch Tumble	0.45
2. Isothermal Roll Forging Cycle	
Load	0.1
Heat-up	0.6
Root injection	0.4
Roll airfoil	0.5 L*
Cool and remove	0.2
3. Die Preparation Cycle	
Cool-down	0.5
Clean die and lubricate	0.6
Set die position	0.3
Set program and check	0.3
4. Isothermal Coin and Twist	
Trim flash	0.25
Grit blast/tumble	0.2
Pickle	0.3
Lubricate, press forge	1.25
5. Blade Finishing	
Tumble	0.1
Electropolish	0.7

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* L is the blade length rolled in inches
Total time: 7 + 0.5 L minutes

6. Root Machine

Crush grind/broach	0.75

For 10% scrap at the final operation (or equivalent higher scrap rates permitted at earlier operation), the time per blade becomes 7.8 + 0.56 L minutes.

For the T55 blade, this becomes a 9.4 minutes per blade for the manufacturing time.

4

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusion drawn from this work is that the program achieved all technical objectives projected at the start of this program. This projection included some technological growth expected with new technology, but indications are that this growth has met and in some areas exceeded expectations. This is reflected in the increasingly favorable cost projections for turbine blades. Because major technology growth is characteristic of new processes but is minimal in older, mature processes, all evidence supports an increasingly favorable technical and economic climate receptive to the introduction of isothermal roll forging of compressor blades.

However, much work remains to be done, most important is the production of engine sets of blades for engine running. This step would provide the necessary confidence in the technology. The next simultaneous step would be the generation of meaningful cost data based on production of engine set quantities in the existing prototype isothermal roll forging machine at Solar Turbines International. This step would provide the confidence needed for future investment, and is critical in today's business climate.

The steps outlined above are strongly recommended to the U.S. Army for support as soon as feasible.

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